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ELECTRICITY METERS AND INSTRUMENT TRANSFORMERS

S. JAMES
M. I. E. E.

ELECTRICITY METERS & INSTRUMENT TRANSFORMERS

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PREFACE

THE advent in Great Britain of the electricity meter as a commercial article dates back to 1880 or thereabouts, and during the intervening years there has been constant improvement in design and manufacture to meet the growing needs of the electricity supply industry. From time to time a new book has appeared dealing with electricity meters, their construction, performance, and testing. Many of these books have been written by engineers connected with the electric supply industry, and few, if any, have been compiled in this country by an engineer closely associated with the manufacture of these instruments. Having spent the greater part of my working life in the designing, manufacturing and testing of electricity meters and accessory apparatus, I have ventured to trespass on this close preserve, in the hope that I may be ble to present some of the facts relating to practical meter work as wed by a manufacturing engineer, and to place on record something iew or about which little has been written hitherto should this be ossible.

Many of the matters dealt with in this volume have been considered n greater detail than is customary in books on meter practice, and it is hoped that this treatment of the subject will be of assistance to the udent and the young engineer without being too wearisome to the ter engineer of more mature experience. Mathematical expression been reduced to a minimum but it was felt that a clear undernding of the working of polyphase and reactive meters could better achieved by some reference to elementary trigonometry and to ector representation. Two-phase metering is uncommon in Great Britain but reference to this subject has been included for the informaion of readers overseas, where extensive use is made of two-phase ipplies.

Considerable practical importance attaches to prepayment meters, f which many are in use. The varieties and types are diverse—much too diverse in my opinion—and it remains to be seen whether simplification and unification of tariffs, which problem is now under consideration by the appropriate authorities, will result in the abandonment of some of the complex devices in use at the present time. The two chapters devoted to prepayment meters are barely sufficient to cover the fringe of a very large subject. The question of tariffs as applied to large power

consumers also has a bearing on the use of reactive meters, kVA meters, and maximum demand indicators, and increasing importance is likely to be attached to the association of these auxiliaries with the ordinary polyphase meter. A separate chapter is devoted to a consideration of each of these classes of instrument.

Very little has been written hitherto concerning summation metering, which was first adopted extensively in connection with the large-scale generation of power and its transmission by means of the Grid to distribution centres covering the whole country. Its purpose in the past has been to measure and record the maximum demand, with the object of determining the charges for power generated or delivered in bulk, and now another important function is to obtain statistical information. The operation and maintenance of the equipment has been largely in the hands of specialist engineers on the staff of the (former) Central Electricity Board. Increasing use is now being made of summation metering for the measurement of bulk supplies to large power consumers, and in this connection is coming more and more into the province of the meter engineer attached to supply undertakings, now the British Electricity Authority Area Boards. The chapter devoted to summation metering provides an elementary introduction to a method having possibilities for extensive use in the future.

Many current and voltage transformers are used in connection with the metering of large power consumers and bulk supplies; a knowledge of their characteristics is essential to the meter engineer and a chapter has been devoted to the consideration of each of these accessories The comprehensive index provided will, it is hoped, assist materially in locating specific subjects.

References have been made in the following pages to British Standards, particularly *B.S. 37: 1937, *Electricity Meters*, and B.S. 81: 1936, *Instrument Transformers*. For many years it has been my privilege to be associated with some of the foremost meter and instrument transformer engineers engaged periodically in the task of drafting and revising these specifications. With a full knowledge of the forethought and care exercised in this work I regard the complete acceptance of their provisions as very desirable in the interests of the industry as a whole. Extracts from these Standards are given by permission of the British Standards Institution, 28 Victoria Street, London, S.W.1, from whom official copies may be obtained.

The field embraced to-day by meter engineering is very wide and I

* See Appendix.

am conscious that in this volume the whole ground has not been covered. It is usual in a handbook dealing with electricity meters to devote space to the testing of these instruments. I consider that this work cannot adequately be covered in these pages and a companion volume is in course of preparation which will be devoted entirely to the testing of electricity meters and instrument transformers.

I wish to express my appreciation of the assistance I have received from manufacturers in supplying information concerning their products, and for the loan of blocks for the purpose of illustration. My thanks are due to the British Standards Institution for permission to quote extracts from Standards. I also acknowledge my indebtedness to management and colleagues at Chamberlain and Hookham Ltd., where I have spent many happy years, and to my associates on numerous Technical Committees, from whom I have derived some inspiration in the preparation of this volume.

Birmingham,
January 1950.

S. JAMES.

CONTENTS

CHAPTER I

SPECIFICATIONS AND LEGAL REQUIREMENTS RELATING TO ELECTRICITY METERS

1.1. The Need for Electricity Meters. An electricity meter is an instrument which measures the consumption of electrical energy in a circuit and registers the amount in appropriate units on a scale or dial which permits an evaluation of the consumption to be made from time to time. The legal unit of electrical energy in this country and in the majority of others is one kilowatt-hour (symbolized kWh) or 1000 watt-hours, although a few make use of a unit of one hectowatt-hour or 100 watt-hours.

When electrical energy was first distributed by supply authorities the provision of means for measuring the consumption became a necessity in order that an equitable charge for the energy could be made. The earlier supplies of electricity which were generated and distributed were direct current and thus direct current meters were the first to be developed. At a later date alternating current supplies became available and suitable means for measuring these had to be devised.

For a long period direct current distribution predominated, but more recently, owing to standardization, alternating current distribution has taken its place and to-day the greater part of this country is fed from alternating current distribution systems. Direct current is still used for traction systems and for many industrial purposes including electro-deposition, electrolytic refining of metals, electric welding and the like. It is also used extensively abroad and consequently there is still a demand for direct current meters. It is true, however, to say that in the case of domestic consumers of electricity in this country by far the greater number receive supplies of alternating current.

In common with all other measuring devices, electricity meters have inherent errors which cannot be entirely eliminated. To achieve absolute accuracy in measurement is impossible although one may approach closely to this ideal. The modern electricity meter is a very accurate instrument and in certain types the errors over a wide range of measurement and under a variety of disturbing conditions can be reduced to negligible proportions. This observation applies particularly with

regard to alternating current meters, which have reached a remarkable degree of perfection, leaving little to be desired.

1.2. Meter Specifications. The earliest regulations concerning the accuracy of electricity meters were contained in Sections 49 to 51 and Section 57 of the Schedule to the Electric Lighting (Clauses) Act, 1899. These regulations have been amended by subsequent legislation and, in addition, specifications relating to the construction and performance of electricity meters have been issued by various authorities. The most important of these specifications is issued by the British Standards Institution. The current issue is entitled **British Standard for Electricity Meters, No.* 37: 1937. Amongst apparatus working in conjunction with electricity meters and having an influence on the accuracy thereof may be mentioned instrument transformers; these also are covered by a specification, the current issue of which is entitled **British Standard for Instrument Transformers, No.* 81: 1936.

These specifications are revised from time to time in order to keep pace with modern requirements, and both are in process of revision at the time of writing this book. The revision is carried out by representatives of the manufacturers of electricity meters and instrument transformers respectively, the British Electricity Authority, the National Physical Laboratory, Government Departments and others who are concerned in the quality and performance of electricity meters. Meters and instrument transformers made to conform to the requirements of these specifications may be regarded as of first-class construction and the accuracy called for is, in general, of a higher order than in comparable specifications issued in other countries.

1.3. Legislation Affecting Electricity Meters. Amending legislation affecting electricity meters was enacted in 1936, which had a very important influence upon meter construction and usage. By Section I of the Electricity Supply (Meters) Act, 1936, Meter Examiners appointed by the Electricity Commissioners under the Act were charged with the examination and certification of meters used or intended to be used in connection with the supply of electricity by authorized undertakers.

Prior to this enactment, supply authorities as they were then, were at liberty to purchase and install any type of electricity meter which in their opinion was capable of functioning satisfactorily. After fixing on consumer's premises, the accuracy of the meter was the sole concern of the undertaker and provided that the consumer did not question

* See Appendix.

the accuracy and that the undertaker was satisfied, the meter might remain undisturbed for a very long period.

Following the placing of the Electricity Supply (Meters) Act, 1936, on the Statute Book, the Minister of Transport fixed the 1st July, 1938, as the Appointed Day on which the provisions of the Act became operative. On this date certain obligations were imposed on Supply Authorities amongst which were the following:

1. To provide Standard and Substandard instruments and accessories in accordance with the specifications for such, as laid down by the Electricity Commissioners.
2. To employ efficient and fully trained personnel for the periodical calibration and checking of this substandard apparatus.
3. To carry out tests on all meters to be installed on consumers' premises after this date, with the object of ensuring that they conform to the statutory limits of error.
4. To submit such meters to examination by a Meter Examiner appointed by the Electricity Commissioners, for verification, certification and sealing.
5. To install on consumers' premises, only such meters as have received the approval of the Electricity Commissioners as regards construction and type and as have been duly certified and sealed.

It follows from Para. 5 above that manufacturers of electricity meters may supply to authorized undertakers, only such meters as have been approved by the Electricity Commissioners, if the meters in question are to be used for measuring the value of the supply to ordinary consumers. In the case of consumers taking a supply of electricity under special agreements, the use of an approved type of meter may not be essential.

The Electricity Act, 1947, resulted in a new constitution of the electricity supply industry and on April 1st, 1948, all supply undertakings, both municipal and privately owned, became State-owned and were merged into the British Electricity Authority. This Authority with fourteen Area Boards and with the North of Scotland Hydro-Electric Board became responsible for the generation and distribution of electricity throughout Great Britain. The powers hitherto exercised by the Electricity Commissioners are now vested in the Minister of Fuel and Power. This Minister is now responsible for the certification of meters and for the approval of meter types.

Prior to nationalization of the electricity supply industry several hundred supply authorities purchased meters and although the meter specification B.S. 37: 1937 was acceptable in the main to the majority many issued their own specification supplementing or modifying the British Standard. The effect of these multitudinous and diverse specifications was to render standardization of manufacture very difficult. The purchase of meters is now undertaken on behalf of the British Electricity Authority by officers representing the fourteen Area Boards. It might have been assumed that in these circumstances one specification acceptable to all the Area Boards would have been agreed to. Such however is not the case and at the present time each Area Board is at liberty to vary its specification quite independently of the others. In this respect the benefits arising from uniformity have yet to be achieved.

1.4. Statutory Limits of Error. The limits of error applicable to electricity meters have been subject to various changes from time to time; in practice the limits of error as laid down in the current issue of the appropriate British Standard (B.S. No. 37: 1937) are accepted. These limits are, generally speaking, closer than the permissible limits implied by Statute, but the legal limits which are expressed in very simple terms cannot make allowance for all the possible disturbing influences which tend to modify the basic errors under standard conditions.

In an authorization by the Board of Trade dated 13th June, 1913, the statutory limits of error were fixed as follow:

For meters in which the maximum current at full load—

(i) does not exceed 3 amperes, the error at any point from one-tenth load to full load must not exceed 3½ per cent., plus or minus.

(ii) exceeds 3 amperes, but does not exceed 50 amperes, the error at any point from one-tenth load to full load must not exceed 2½ per cent., plus or minus.

(iii) exceeds 50 amperes, the error at any point from one-twentieth to one-tenth load must not exceed 2½ per cent. plus, and at any point from one-tenth load to full load must not exceed 2½ per cent., plus or minus.

These allowable limits of error were applicable to direct-current meters and single-phase alternating current meters.

In 1937, the Electricity Commissioners issued an instruction as follows:

Electricity (Supply) Acts, 1882 *to* 1936.
Limits of Error for Meters.

In virtue of the powers exercisable by them under the Electricity (Supply) Acts, 1882 to 1936, and Orders made thereunder and Local Acts relating to the supply of electricity, the Electricity Commissioners HEREBY ALLOW the following limits of error, namely an error not exceeding $2\frac{1}{2}$ per cent. plus or $3\frac{1}{2}$ per cent. minus at any load at which the meter may be operating, for meters, the construction and pattern of which have already been or may hereafter be approved under the Acts and Orders aforesaid as meters capable of ascertaining the value of the supply on direct-current or alternating-current circuits.

The limits of error hereby allowed shall supersede the limits of error allowed by the Board of Trade by an authorization dated 13th June, 1913, and the said authorization shall cease to have effect as from the date hereof without prejudice to anything done or suffered thereunder.

Signed by order of the Electricity Commissioners this 14*th day of September*, 1937.

A. E. MARSON,
for Secretary to the Electricity Commissioners.

In comparing the latest permissible limits of error with those previously in force, the following points may be noted. In the authorization of 1913, the Board of Trade evidently took cognizance of the facts that:

(i) direct current meters of the smallest current ratings could not be expected to register as accurately as the larger current ratings;
(ii) meters, both direct current and alternating current, could not be expected to register as accurately on low loads as on high loads;
(iii) meters, both direct current and alternating current, could not be expected to register within acceptable limits of error at any loads below a certain minimum.

It may be true that, theoretically, some types of electrolytic meter for use on direct current circuits were capable of conforming to the limits imposed, but such meters suffer, as a class, from certain disadvantages which render them unsuitable or unacceptable for many purposes.

The Electricity Commissioners in their instruction issued in 1937, stipulate that a meter shall register within the prescribed limits of error *at any load at which the meter may be operating*, and they make no

distinction between meters for small current ratings and meters for large current ratings. This stipulation implies that no matter how large or how small the load, or what disturbing influences are present such as abnormal temperature, voltage, frequency or the like, the meter must register within the prescribed limits of error under all conditions. In the present state of the metering art, and notwithstanding the high degree of perfection which has been reached in many types, there is probably no meter which can in all circumstances satisfy this requirement and at the same time conform to all the other necessary requirements as regards constructional features.

In the foregoing statement no suggestion is made that existing meters are unsuitable for performing their functions. Such an inference would be ridiculous in the extreme. On the other hand the Electricity Commissioners were fully informed as to the capabilities and limitations of modern meters. It may be presumed therefore, that the phrasing of the instruction relating to limits of error is intended to avoid legal difficulties which might conceivably arise in certain circumstances had the Board of Trade authorization of 1913 remained in force.

A meter may be expected to give its best performance and to function consistently at loads from ten per cent. upwards. Below this point the stability is not so good and disturbing influences which may develop in course of time are more likely to result in inaccurate registration at low loads. It follows therefore, that in selecting a meter for any given installation, some regard should be paid to the probable minimum load as well as the possible maximum. It is extremely unlikely that any consumer, other than the small lighting consumer, will switch on the whole of the connected load at the same time, and it is desirable in the interests of good metering to pay some regard to the maximum continuous rating of the meter as well as the maximum probable loading of the installation.

1.5. Rating of Meters. Arising out of the previous paragraph, it is appropriate here to refer to the current rating of meters and to the relationship existing between rating and overload capacity. In B.S. 37: 1937, a number of clauses refer in some manner to the rating of meters. Clause 10 defines Marked Current as "the current in amperes marked on the nameplate of the meter". Clause 37 specifies the limits of error with different currents, expressed as a percentage of the marked current, and Clause 43 specifies the duration of permissible excess currents for various types of meter with reference to the marked current.

In the case of direct current meters, limits of error are specified for current loadings up to 125 per cent. of the marked current. Most meters will safely carry for a limited period currents in excess of this value, but the errors of the meter during this period may be outside the guaranteed limits. Whole-current meters up to a marked current of 50 amperes will carry without injury and without the accuracy being permanently impaired, an excess current of 100 per cent. for thirty minutes. Whole-current meters above 50 amperes, up to and including 1,000 amperes, and also all meters with shunts up to 1,000 amperes, will in similar circumstances carry an excess current of 50 per cent. for thirty minutes. Whole-current meters and meters with shunts above 1,000 amperes will carry an excess current of 25 per cent. for thirty minutes.

In the case of alternating current meters the same conditions apply as for direct current, but there is an additional class of single-phase meter referred to in B.S. 37: 1937, as " Long-Range ", for which limits of error are specified up to 200 per cent. of the marked current. In addition, it is specified that a long-range meter shall not be injured and its accuracy shall not be permanently impaired by an excess current of 100 per cent. above marked current, i.e. by 200 per cent. of the marked current carried continuously.

Prior to the introduction of the long-range meter, the working range of a single-phase meter was from 125 per cent. to 5 per cent. of the marked current. Expressed as the ratio of the maximum to the minimum load, this corresponds to a range of 25 to 1. This working range still applies to whole-current single-phase meters of 100 amperes rating and to all meters operated from current transformers.

The extension of the range of measurement during the last twenty years has been progressive and at the time of publication of B.S. 37: 1937, meters having a range of 40 to 1 were in common usage. At the present time the majority of meters have a range of at least 60 to 1 and in one country a range of 80 to 1 is recognized. It cannot be assumed that progress has ceased and that this represents the ultimate limit, and there is surely something illogical in a system of rating which implies that a piece of apparatus, whether it be a meter, a generator or a power transformer, can operate continuously at three or four times its marked current, where the marked current is supposed to represent the full load condition.

Because of this continued extension of the working range and the illogical system of rating with which it has been associated, the current markings of single-phase meters have become anomalous and give no

precise indication of the maximum continuous rating. For example, a meter used to be capable of carrying a continuous overload of 25 per cent. which later was increased to 100 per cent. and has now reached 200 per cent. or more. The fact is, of course, that the maximum continuous rating is no greater to-day that it has ever been but the range of accurate measurement has been extended in the downward direction.

By comparison with a meter having a range of 25 to 1, the modern meter having a nominal range of say 60 to 1 is accurate from 125 per cent. load down to 2 per cent. load. Expressed in this manner the achievement appears less spectacular than is suggested by stating that the range is from 300 per cent. load down to 5 per cent. It may be anticipated that when the next revision of BS. 37: 1937 is completed, a more logical system of rating will have been adopted, which will remove the anomaly to which reference has been made.

1.6. Approved Types of Electricity Meters. Except where an agreement between the supply authority and the consumer exists to the contrary, all meters to be installed on consumers' premises must be of construction and pattern approved by the Ministry of Fuel and Power (formerly Electricity Commissioners). Request for approval is made by the manufacturer or his agent, who submits a number of samples of the type in question, accompanied by drawings and specifications giving full details of the construction, to the Director of the National Physical Laboratory, Teddington. Here the meter is critically examined and tested, and is then kept under observation for a considerable period in order to make certain that it is capable of complying with all the conditions laid down in the appropriate specifications as regards suitability, accuracy, and permanence of calibration. At the end of this period a report on the meter is submitted to the Minister of Fuel and Power, who, provided that he is satisfied in all respects, may grant the desired approval.

Prior to the passage of the Act of 1936, many types of meter were in use which had not been submitted for approval. Others which had been at one time approved, had been modified in various ways, thus invalidating the original approval and had not been re-approved. In order that use of these types might be continued after the Appointed Day (1st July, 1938), approval or re-approval became necessary. The normal period required for the granting of approval is from one to two years, but owing to the unusually large number of meter types submitted in a limited period, the Electricity Commissioners were at that time unable to cope with the enormous amount of work involved.

Accordingly, Provisional Approval was granted in many cases after a comparatively short period, provided that the initial performance was satisfactory. This Provisional Approval was subject to confirmation or rejection at a later date when circumstances permitted a more thorough investigation to be made.

Certain types of meter were regarded by the Electricity Commissioners as unsuitable for approval. These included one particular type of direct-current ampere-hour meter, namely the commutator motor meter which had been used to a limited extent in this country, mainly if not wholly on account of its low price. It has been and still is used extensively on the Continent of Europe where the standards of accuracy demanded by the authorities are much inferior to those enforced in Britain. It is probable that approval would be granted for meters of this type if they could be made sufficiently accurate and reliable as to conform to the specifications laid down, but it is significant that, so far as the author is aware, no such meters have yet been produced.

1.7. Periodical Re-testing of Meters. The Electricity Supply (Meters) Act, 1936, provided for the periodical re-testing of electricity meters installed on consumers' premises, at intervals not exceeding ten years from the date when last certified. This provision minimizes the possibility of errors going undetected for a long period if such should develop after the meter has been installed.

A further provision of the Act required that meters which were installed on consumers' premises prior to the Appointed Day (1st July, 1938), shall be removed within ten years of that day if they are of a type which had not been approved. This period has now been extended to fifteen years. All meters installed prior to the Appointed Day were regarded as certified meters although many such were of types which would not in other circumstances be regarded as satisfactory. Thus, this provision imposes a time limit of fifteen years for the use of possibly inaccurate meters.

1.8. Meter-Testing Stations. By Section 2 of Electricity Supply (Meters) Act, 1936, it became the duty of Electricity Supply Authorities, referred to in the Act as Authorized Undertakers, to provide and maintain in proper condition, such suitable apparatus as prescribed or approved by the Electricity Commissioners, for the examination, testing and regulating of meters used or intended to be used in connection with the supply of electricity, and to afford to Meter Examiners all necessary facilities for the use of such apparatus.

Since the Electricity Supply (Meters) Act, 1936, became effective,

the Electricity Supply Industry has been nationalized and the obligations of the Authorized Undertakers have been taken over by the British Electricity Authority acting through fourteen Area Boards. The powers exercised hitherto by the Electricity Commissioners are now exercised by the Minister of Fuel and Power. In the references to the Act which follow, and in order to avoid confusion, the words " British Electricity Authority " have been substituted for " Authorized Undertaker " where these occur in the original, and likewise the words " Minister of Fuel and Power " have been substituted for " Electricity Commissioners ".

Particulars of the apparatus approved by the Minister of Fuel and Power as Standard or Sub-standard Apparatus for use in Meter Testing Stations are set out in an Approval dated 4th June, 1937. Copies of this Approval are obtainable from His Majesty's Stationery Office, Kingsway, London, W.C.2. The Approval specifies the requirements as to construction and performance with which all Standard and Substandard Apparatus acquired after 1st June, 1937, must comply to secure approval. It is so worded that it is not made compulsory for every Testing Station to be provided with the whole of the approved Standard and Substandard Apparatus, or to carry out the retesting of the whole or any portion of its own Substandard Apparatus. This work may be carried out by one Testing Station on behalf of another, with the approval of the Minister of Fuel and Power.

Meter Examiners are directed to satisfy themselves from time to time that the apparatus in Testing Stations is properly maintained and in proper functioning order, and for this purpose they may make such check tests as they may consider necessary. It does not form part of the statutory duties of Meter Examiners, to carry out any of the periodical retestings prescribed in the Approval.

1.9. Testing Meters for Certification. The Approval sets out the method of meter-testing and the actual meter tests for the time being approved by the Minister of Fuel and Power for the purposes of certification of meters by the Meter Examiners. The Minister of Fuel and Power may in appropriate cases modify the methods of testing, or actual tests for the time being approved, or may approve other methods and tests. The general procedure with regard to the testing of meters and the subsequent certification by the Meter Examiners is laid down as follows:

(i) The meters are tested at the Testing Stations in accordance with the approved methods described in Appendix " B " to the

Approval or such modifications thereof as may be allowed in particular cases.

(ii) The meters when tested and before being eligible for certification require to be duly sealed by or on behalf of the undertakers in a manner approved by the Minister of Fuel and Power.

(iii) Particulars of each meter and the results of the tests set out in a form approved by the Minister of Fuel and Power, then require to be submitted to the Meter Examiner for examination.

(iv) If and when a Meter Examiner is satisfied (a) as to the result of such examination, and after such tests as he may deem necessary or as he may be directed by the Minister of Fuel and Power to make, that the meters have passed the tests for the time being in force in relation to the Testing Station; (b) that the meters are duly sealed; and (c) that the meters are capable of ascertaining the value of the supply within the limits of error allowed, and are of a construction and pattern approved by the Minister of Fuel and Power, the Meter Examiner is then entitled to certify the meters.

CHAPTER II

DIRECT-CURRENT METERS

2.1. Functions of a Direct Current Meter. A direct current meter is an instrument intended for the measurement of electrical quantity in a direct current circuit. There are two main classes of direct current meters, (i) ampere-hour meters and (ii) watt-hour meters. An ampere-hour meter measures the product of the current in amperes flowing in a circuit and the time in hours during which the flow is maintained. A watt-hour meter measures the product of the power in watts and the time in hours during which the flow of power is maintained.

2.2. Direct Current Ampere-hour Meters. Ampere-hour meters are used by electrical undertakings for measuring the supply of electricity to domestic and industrial consumers. These undertakings are under a statutory obligation to maintain the voltage at consumers' terminals at a declared value within close limits; assuming that the supply voltage is maintained at the declared value, an ampere-hour meter can be calibrated to register in terms of kilowatt-hours at this voltage. This principle is accepted as satisfactory in most countries where the voltage at consumers' terminals is maintained within narrow limits of the declared voltage, and since direct current ampere-hour meters are, in general, more reliable and less costly than direct current watt-hour meters the practice has much in its favour.

In addition to the foregoing, ampere-hour meters are used for measuring the current consumption in battery charging, electro-deposition and other electrolytic or industrial processes and in some instances they exercise a controlling function over these operations. Many types of ampere-hour meter have been manufactured in the past, the most important being electrolytic meters and motor meters. Theoretically the former are capable of very accurate registration but in practice the working results are not so good as with motor meters, and the latter are preferred by most supply authorities.

2.3. Electrolytic Meters. The principal field for the use of electrolytic meters has been in connection with the measurement of supplies of current to the smallest domestic consumers of electricity. The advantages claimed for this type are (i) low capital cost, (ii) simple construction, (iii) no moving parts, (iv) registration on the smallest current,

(v) equal accuracy at all loads. The disadvantages are (i) fragility (ii) need for periodical refilling or resetting with consequent loss of record, (iii) a scale difficult to read accurately, (iv) high voltage drop, (v) impossibility of carrying out repairs, (vi) high service costs, (vii) non-conformity to modern requirements as regards sealing.

Electrolytic meters are now of little more than historical interest and as they are no longer used extensively in this country only brief reference will be made to representative patterns. These are (i) the water decomposition type as devised by Bastian, (ii) the metal deposition type as devised by Wright, and (iii) the gas deposition type as devised by Holden. The Bastian meter went out of production many years ago, but the Wright meter is still made in Britain. Manufacture of the Holden meter on a small scale took place for a few years, after which a Continental firm acquired the patent rights, and development and manufacture continued in Germany with a fair amount of success. The factory in which the meter was made was in what is now Russian occupied territory and consequently no information is available concerning its success or otherwise.

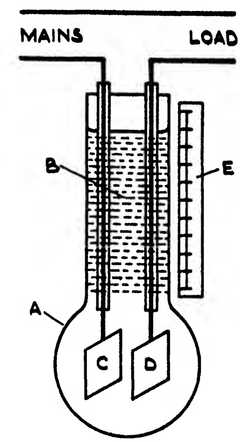


FIG. 1.—Bastian electrolytic meter.

2.4. Bastian Electrolytic Meter. In this meter, which was manufactured by the Bastian Meter Co., water is decomposed by the passage of electricity through an electrolytic cell. The form taken by the meter is shown in Fig. 1. A glass vessel *A* consisting of a tube of uniform bore terminating in a bulb at its lower extremity contains the electrolyte *B*. Two nickel electrodes *C* and *D* occupy the bulbous portion and are connected by insulated nickel rods to the top of the meter, at which point they are joined in series with the consumer's circuit; the electrolyte consists of a weak solution of caustic soda in water. The addition of caustic soda is made in order to reduce the resistance of the meter, since pure water is a non-conductor of electricity. A scale *E* graduated in kilowatt-hours at the declared voltage of the supply is fitted on the exterior of the glass vessel.

When the meter is installed on consumer's premises, it is filled with electrolyte up to the zero division at the top of the scale, and to prevent evaporation a thin layer of paraffin is provided on the surface of the

electrolyte. The passage of current between the electrodes *C* and *D* decomposes the water into its constituent elements, oxygen and hydrogen, at a rate proportional to the current flowing at any instant. These gases escape from the meter, and the volume of the electrolyte diminishes at the rate of 0·3464 cubic cm. per ampere-hour. This reduction in volume is a measure of the kilowatt-hours used in the consumer's circuit and can be read against the scale. As the volume of the electrolyte diminishes the density increases, since it is only the water which is decomposed: it becomes necessary from time to time to replace the water which has been lost, and to reset the scale to zero. This is easily accomplished as the scale is made adjustable for this purpose. The resetting is a disadvantage since the record of the previous reading is destroyed, and in the event of a dispute with the consumer no proof can be produced as to the correctness of the last observation.

Owing to the resistance of the electrolyte the drop in voltage across the meter terminals, due to the passage of full-load current, is of the order of 3 volts; in addition, there is a back e.m.f. of 1·5 volts, thus making a total loss of 4·5 volts, approximately. The meter cannot be shunted, and consequently carries the whole of the current in the circuit; this limits the use of the meter to small installations. When current is passing a certain amount of frothing takes place at the surface of the electrolyte, making it difficult to take a reading, and in some cases it is necessary to switch off the load before an observation can be made.

2.5. Wright Electrolytic Meter. In this meter, made by the Reason Manufacturing Co., mercury is deposited on a cathode by the passage of current through an electrolyte, and falls into a graduated measuring tube. The rate of deposition of mercury is proportional to the current passing through the cell, and a scale adjacent to the measuring tube enables the number of kilowatt-hours passed through the circuit to be observed.

The essential parts of this meter are shown diagrammatically in Fig. 2. A glass vessel *A* consisting of a vertical tube of uniform bore, on the upper end of which an enlarged chamber is formed, is nearly filled with an electrolyte *B*. This electrolyte consists of a solution of the double iodide of mercury and potassium. An iridium cathode *C* is fixed above the top of the vertical measuring tube. A pool of mercury *D* in the lower portion of the chamber forms the anode of the cell. In series with the cell is a resistance *E*, the two being connected across

the shunt *F*, which has an adjustable portion *G*. When current is passed through the shunt, a minute fraction is by-passed through the cell, and mercury is deposited from the solution on to the cathode. An equal quantity of mercury passes from the anode into solution so that the total amount of free mercury is always the same.

The mercury deposited on the cathode cannot adhere thereto, and falls in a fine stream down the measuring tube, forming a column of mercury *H*. The graduated scale adjacent to the column gives the corresponding value in kilowatt-hours at the voltage for which the meter has been calibrated. The resistance of the cell varies inversely with the temperature and to compensate for this the resistance *E* in series with the cell is so proportioned that any reduction in cell resistance is exactly balanced by an increase in the resistance of *E*, the sum of the two being always the same. In this manner the meter is compensated for temperature errors.

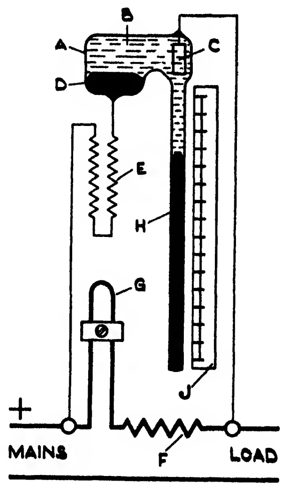


FIG. 2.—Wright electrolytic meter.

In series with the shunt *F*, a loop *G* having a sliding adjustable bridge permits the voltage drop across the meter to be varied. By this means the meter may be calibrated for any selected voltage within a limited range. The glass vessel is mounted on a supporting frame which is hinged near the top in such a manner that the tube can be inverted. When the meter is first installed, it is necessary to transfer any mercury there may be in the measuring tube, to the pool forming the anode; this is done by inverting the tube which permits the mercury to gravitate to the anode.

After a period of use on consumer's premises the measuring tube will contain a column of mercury, and when this approaches near the top of the tube it becomes necessary to reset the meter in the manner already described. In order to avoid frequent resetting of the meter, it may be fitted with a syphon whereby the column may be syphoned out automatically into another measuring tube of larger volume, each time 100 kilowatt-hours have been registered. This second measuring tube is graduated in steps each of 100 kilowatt-hours, so that a total

of 1,000 kilowatt-hours or more may be registered before manual resetting becomes necessary.

This type of meter is always shunted, and the voltage drop across the meter terminals at full load does not usually exceed 1 volt. The current through the cell is only a few milliamperes and the back e.m.f. is approximately one-tenth of a millivolt. The error introduced by this back e.m.f. increases as the load is reduced but in any circumstances it may be regarded as negligible.

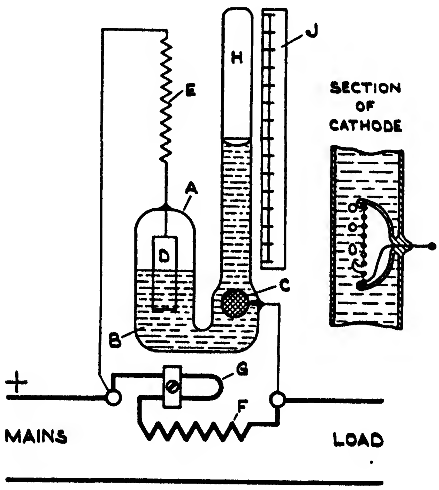


FIG. 3.—Holden electrolytic meter.

2.6. Holden Electrolytic Meter. In this meter which was made by Chamberlain & Hookham Ltd., hydrogen gas is liberated from an electrolyte at the cathode of an electrolytic cell, the rate of liberation being proportional to the current passing through the cell at any instant. The hydrogen is collected in a measuring tube and an adjacent scale permits the total consumption in kilowatt-hours to be read.

A diagrammatic arrangement of the meter is shown in Fig. 3. A hermetically-sealed glass vessel *A* consisting of a bulb connected at its lower portion to the base of a vertical measuring tube is partly filled with an electrolyte *B*, consisting of dilute phosphoric acid. A cathode *C* at the base of the measuring tube consists of a small glass thimble, across the open end of which a gold gauze disc is sealed; a fine platinum

wire is attached to the gold gauze and is carried through the thimble and through the wall of the measuring tube for connection to the external circuit. A section of the cathode is shown separately and it will be noted that the cavity in the thimble, behind the gold gauze, is filled with gas.

An anode *D*, consisting of a strip of platinum foil, is supported in the bulb in such a manner that it is partly immersed in the electrolyte and partly exposed in the gas space above the liquid. The anode is connected by a platinum wire, passing through the wall of the bulb to a fine wire resistance *E*, of 10,000 to 20,000 ohms. The cell with its series resistance is connected across the terminals of a shunt *F*, having an adjustable portion *G*. When full-load current is passed through the shunt a very small fraction—one tenth of a milliampere or less—passes through the cell. Hydrogen is liberated at the gold gauze cathode and escapes into the thimble. This raises the gas pressure in the thimble and hydrogen is forced through the mesh of the gauze, escaping in minute bubbles and rising up the measuring tube. The hydrogen collects in the upper portion of the tube at *H*, and the graduated scale *J* adjacent to the gas column shows the number of kilowatt-hours expended in the circuit, at the voltage for which the meter has been calibrated.

The platinum anode *D* is coated with a deposit of platinum black, and readily absorbs hydrogen into its porous surface. The gas space above the level of the electrolyte in the bulb is filled with pure hydrogen and as the portion of the anode above the surface of the liquid is exposed to this gas the coating of the anode becomes saturated with hydrogen. When current passes through the cell, hydrogen is liberated at the cathode and oxygen in the pores of the anode. But the pores of the anode are at all times saturated with hydrogen, and the nascent oxygen immediately combines with this to form water. The number of hydrogen atoms liberated at the cathode is exactly equal to the number of hydrogen atoms combined at the anode, consequently no free oxygen exists in the cell and the density of the solution remains constant; also the total volume of the hydrogen does not vary since an increase in the volume of the gas in the measuring tube is accompanied by an exactly equal decrease in the volume of the gas in the bulb.

When the measuring tube becomes full it is necessary to reset the meter to zero. The glass vessel is secured to a hinged frame in such a manner that the vessel can be inverted or inclined; this permits the hydrogen which has collected in the measuring tube to escape into the

bulb and the measuring tube fills with electrolyte. On restoring the vessel to its normal position it is again ready for use.

The resistor E is of the same material as the shunt F and has a negligible temperature coefficient. The resistance of the cell varies with temperature but the variation is so small by comparison with the resistance of E that for practical purposes the meter may be regarded as having no temperature error. The cell has no back e.m.f. and the meter will register the minutest current. The potential drop across the shunt at full load is less than 1 volt, and can be adjusted by movement of the bridge piece on the loop G to calibrate the meter for any declared voltage. The meter follows a straight-line law from the smallest load to the greatest overload which the shunt is capable of carrying.

2.7. Commutator Motor Ampere-Hour Meters. The commutator motor ampere-hour meter has never been very popular in this country although it is used extensively on the Continent. Its chief claim for consideration has been its low price but the performance of which it is capable is much inferior to that of a mercury motor meter. The permissible limits of error on the Continent for a meter under service conditions are wider than in England and now that the Ministry of Fuel and Power exercises some supervision over the working errors of meters, supply authorities find it difficult to obtain certification for meters of this class. It is still possible to calibrate some types of commutator motor meters to conform to the permissible limits of error, but deterioration is rapid and within a few days or even hours the low-load errors may have changed to such an extent that they exceed the prescribed limits.

Commutator motor meters have been made by many different manufacturers and all work on the same principle although the constructional details may differ. A diagrammatic arrangement of the elements embodied in a commutator meter is shown in Fig. 4. An armature A mounted on a vertical spindle B revolves between the poles of two permanent magnets $C1$, $C2$. The bottom pivot of the armature shaft rests on a jewelled bearing D and the top pivot runs in a pivot hole in a plate or screw forming the top bearing; both pivots are highly polished to reduce friction to a minimum.

The armature consists of three flat coils of fine wire housed between two thin aulminium discs and insulated therefrom. The coils are spaced 120° apart and each occupies approximately one-third of the area of the disc; each disc has a lip around the circumference and the one lip fits inside the other, the outer one being spun over to prevent the two

from coming apart. One end of each of the three coils is connected to a three-part commutator *E* mounted on the vertical spindle and the other three ends are connected together. The commutator is frequently made of gold or a gold-silver alloy to prevent oxidation of the contact surface, and the diameter is kept as small as possible in order to minimize friction. Two sets of brushes *F*1, *F*2, consisting of fine gold or silver wires, sometimes having platinum tips, rest lightly on the commutator.

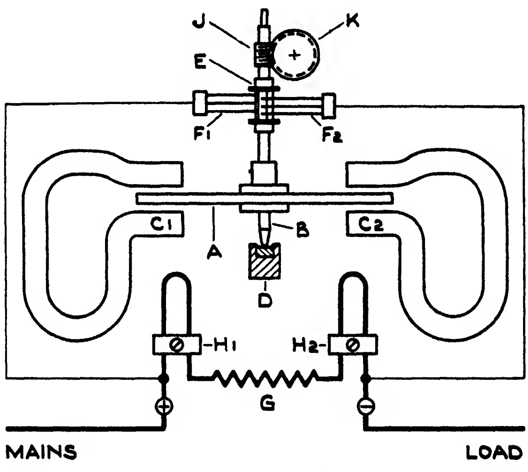


FIG. 4.—Diagrammatic arrangement of commutator A-H meter.

A shunt *G* with loops *H*1, *H*2 for adjustment purposes is connected across the meter terminals and carries the main current. The brushes *F*1, *F*2 are connected across the extremities of the shunt and conduct a small proportion of the main current to the armature coils. The coils are so placed in the armature that when carrying current they set up a vertical magnetic field which reacts with the vertical field between the poles of the permanent magnets *C*1 *C*2 and causes rotation of the armature. A worm *J* on the armature spindle engages with a worm-wheel *K* and communicates the revolutions of the armature to the meter register (not shown); alternatively a pinion and wheel may take the place of the worm and worm-wheel.

The average torque or driving force exerted by the armature is proportional to the current in the main circuit. The torque at any instant depends upon the position of the armature coils relative to the

magnet poles and consequently rises to a maximum value and falls to a minimum three times in each revolution of the armature. At high loads the armature tends to rotate at a uniform speed if the load is constant, but at low loads the variation in speed due to the variation in torque is easily discernible.

Immediately the armature commences to rotate, eddy currents are set up in the aluminium discs forming the upper and lower casing of the armature, due to the discs cutting through the magnetic fields of the permanent magnets. These eddy currents react with the magnetic field, which causes them to set up a braking action tending to oppose rotation; when the braking force is equal to the driving force the armature will continue to run at a constant speed. The driving force is proportional to the main current and the braking force is proportional to the speed

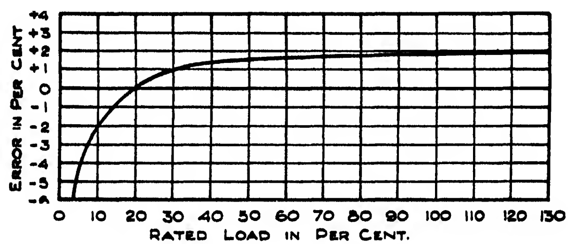


FIG. 5.—Characteristic curve for commutator A-H meter.

of the armature; consequently the speed is proportional to the current in the absence of any disturbing factors.

A characteristic curve giving the typical errors of a commutator motor ampere-hour meter is shown in Fig. 5. It will be noted that the meter registers with a plus error at high loads, the error becoming less as the load is decreased until finally it becomes minus at low loads. At 125 per cent. load the error of the meter approaches the permissible limit in the positive direction, while at 5 per cent. load the error exceeds the permissible limit in the negative direction. At 20 per cent. load the error is practically zero, but on a falling load the error increases rapidly in the negative direction due to the effects of friction. The main source of friction is the pressure of the brushes on the commutator and no matter how lightly these are set, friction at this point cannot be eliminated. There is also some friction in the top and bottom bearings and when the armature is revolving at high speed the effect of air friction cannot be neglected.

Another disturbing factor is the contact resistance between brushes and commutator. If the brushes are set with a light pressure in order to minimize the error due to friction, contact resistance will be high and will increase rapidly with time. In addition, on high loads, light pressure results in sparking which roughens the surface of commutator and brushes. Thus it is difficult to strike the happy medium between excessive friction on the one hand and excessive contact resistance on the other. Both factors are detrimental to good performance on low loads and both tend to increase with time; the result in any case is instability and uncertainty with regard to low-load accuracy.

The effect of a short-circuit on consumer's premises, due for example to a faulty lamp, often results in the brushes being burned up or to fusion of the commutator. The armature usually rotates at high speed on full load—100 to 150 revolutions per minute—and owing to its considerable weight, wear and tear on the bottom pivot and jewel is considerable. In these circumstances it is not surprising that the life of a commutator motor ampere-hour meter is short and that accurate registration, even if achieved initially, cannot be maintained for a reasonable period of time.

2.8. Mercury Motor Ampere-Hour Meters. The first mercury motor meter was invented by Ferranti in 1883. It consisted of a shallow circular chamber containing mercury located between the poles of an electromagnet. The chamber lay in a horizontal plane and the magnetic field traversed it in a vertical direction. The walls of the chamber were covered with insulating material and the current to be measured was carried radially by the mercury, entering at the circumference of the chamber and leaving at the centre. The coil of the electromagnet was in series with the mercury chamber and when current was passed through the meter, the mercury rotated in the chamber, due to the reaction between the field set up by the electromagnet and the current through the mercury.

The torque produced by this combination was proportional to the square of the current. The brake was due to fluid friction between the rotating mercury and the walls of the chamber and varied approximately as the square of the speed of rotation. The resultant of these two opposing forces was a speed approximately proportional to the current, over a limited range. If it was desired to modify the speed it became necessary to dismantle the meter in order to expose the walls of the chamber, which were corrugated radially. By making the walls smoother the speed could be increased and by roughening them could

be reduced. Light vanes mounted on a vertical spindle and immersed in the mercury served to communicate motion from the mercury to the register.

By comparison with other meters available at the time, this early Ferranti meter was a great advance in the art, and it held the field until 1891 when Hookham introduced his mercury motor meter. Since that date, all successful meters of this type have utilized the fundamental principles which were embodied in Hookham's invention. It incorporated for the first time a copper disc immersed in a mercury chamber and placed in the field of a permanent magnet. Current was passed radially through the disc and reacting with the field of the permanent magnet, set up a torque which produced rotation of the disc and the spindle on which it was mounted. The driving disc was provided with radial slits in order to confine the current to a radial path and thus to increase the torque. A second disc mounted on the same spindle and outside the mercury chamber cut through a magnetic field in parallel with the field acting on the driving disc. This second disc constituted an eddy current brake, the braking effect being proportional to the speed of the rotor. Thus the speed of rotation of the disc was proportional to the current if one ignored disturbing factors such as friction. Actually the fluid friction between the driving disc and the mercury in which it was immersed did constitute a disturbing factor of some importance and since this friction increased with the load at a rate proportional to the square of the speed of the rotor it became necessary to apply a compensating influence. Hookham overcame this difficulty by means of a correction coil wound on that part of the magnetic circuit which carried the flux acting upon the brake disc. The correction coil which was connected in series with the mercury chamber opposed the passage of the braking flux and consequently reduced the effect of the brake as the load increased. The amount of correction applied was proportioned so that the error curve of the meter became approximately flat on the higher loads.

It is possible by over-compensating a meter for fluid friction, to raise the curve at the higher loads so that the meter is registering fast on overloads. With over-compensation the shape of the upper part of the curve would resemble that of a commutator meter as shown in Fig. 5. As a matter of fact, however, it is advantageous for the meter to be slightly under-compensated and Fig. 6 gives a typical characteristic curve for a modern mercury motor ampere-hour meter. This shows an error of 1·5 per cent. minus at 125 per cent. load and 1·5 per cent. plus

at 25 per cent. load. From this point downwards the meter tends to become slower and at 5 per cent. load the error is 1·0 per cent. minus. This under-compensation, by raising the middle part of the curve,

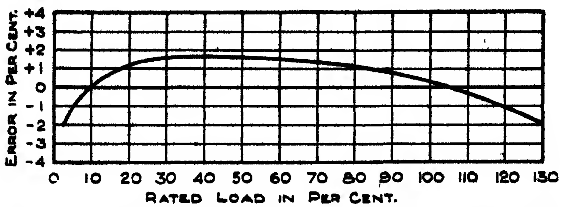


Fig. 6.—Characteristic curve for mercury motor A-H meter.

permits the errors throughout the working range of the meter to be kept within a comparatively narrow band.

2.9. Ferranti Direct Current Ampere-Hour Meter. The general arrange-

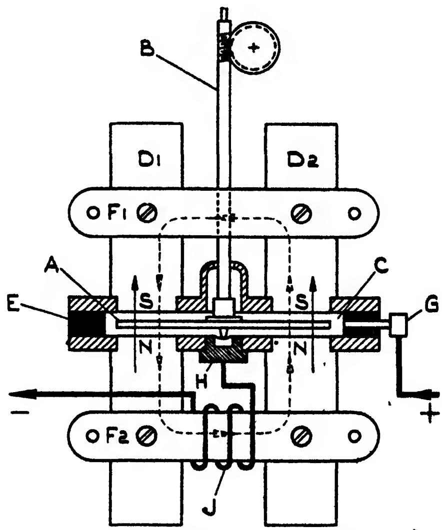


Fig. 7.—Ferranti direct-current A-H meter, general arrangement.

ment of a modern Ferranti direct current ampère-hour meter is shown diagrammatically in Fig. 7. An amalgamated copper armature *A* mounted on a vertical spindle *B* is contained in a chamber *C* and is free to rotate between the poles of two permanent magnets *D*1, *D*2. These magnets are provided with pole-pieces *NS* secured in the plates

forming the top and bottom of the chamber *C* which latter is filled with mercury. A ring of insulating material *E* separates the two plates and maintains the pole-pieces at the correct distance apart.

The two magnets of substantially equal strength are magnetized to give south poles at the top of the chamber and north poles at the bottom. Two iron bars *F*1 *F*2 are secured to the magnets near their polar extremities and since the points of attachment are approximately at equal magnetic potentials, very little flux will be carried by the bars when no current is passing through the meter. A copper contact *G* passing through the insulating ring surrounding the chamber serves to conduct current from the positive terminal of the meter into the armature via the intervening mercury. A copper contact *H* in the bottom plate of the chamber conducts the current from the centre of the armature via the intervening mercury, to a correction coil *J* consisting of a few turns of wire wound on the bar *F*2, and thence to the negative terminal of the meter. The interior surface of the chamber is insulated to prevent leakage of current through the metal plates and the exposed surfaces of the contacts *G* and *H* are amalgamated to reduce contact resistance. The lower bearing of the armature consists of a ball-pointed steel pivot resting in a sapphire cup set in the copper contact *H* and this latter may be removed for examination of the jewel if desired.

When current passes through the meter it travels from contact *G* in a radial direction through the armature to contact *H* and is concentrated in the area between the poles of the right-hand magnet *D*2. The interaction between the current in the armature and the magnetic field in which it is situated sets up a driving torque which is proportional to the product of the current and the magnetic field. This torque causes the armature to rotate and in so doing, eddy currents are induced in the copper in such a direction as to oppose rotation; a balance is reached when the driving force is opposed by an equal and opposite braking force and at this point a steady speed of rotation will be maintained. In the absence of any disturbing influences the speed would be proportional to the current passing through the meter at all loads, but owing to frictional retardation strict proportionality cannot be maintained under all conditions. Friction in the bearings and in the gearing associated with the register result in a falling-off in registration at low loads and this can only be minimized by reducing friction wherever possible.

At loads above 25 per cent. of rated current the effects of fluid friction between the armature and the mercury in which it is immersed

can be observed. The ratio of speed to current becomes progressively less as the current is increased above this value and consequently the registration of the meter at high loads would tend to become slow. This tendency is compensated for by means of the correction coil *J*. This coil is wound so that a magneto-motive force is set up in the lower iron bar *F*2, which results in an increase in the flux crossing the airgap between the poles of the right-hand magnet *D*2 and a corresponding reduction in the flux crossing the airgap between the poles of the left-hand magnet *D*1. The total flux cutting through the armature is the same under all conditions but since the driving torque increases at a greater rate than the meter current, the tendency for the meter to register too slow on high loads is avoided.

The arrows shown in dotted lines in the diagram indicate the direction of the flux due to the correction coil and the full-line arrows indicate the direction of the main flux. It will be noted that all the driving torque is due to the right-hand magnet *D*2, but since the armature rotates in the field of both magnets each contributes to the total braking effect exerted. In order to enable slight adjustment of the speed of the armature to be made, an adjustable magnetic shunt (not shown) is fitted across the poles of the left-hand magnet *D*1. By moving the shunt nearer to the magnet poles, the braking effect is reduced and the speed of the armature is increased. A registering mechanism is driven by a worm located at the top of the armature shaft and by means of change wheels the meter can be calibrated to register in terms of kilowatt-hours at the declared voltage of the system for which it is intended.

2.10. Chamberlain and Hookham Direct Current Ampere-Hour Meter. The general arrangement of a Chamberlain and Hookham direct current ampere-hour meter is shown in Fig. 8. An armature consisting of a copper disc *D* mounted on a vertical spindle *F* is contained in a chamber filled with mercury; the surface of the armature is platinum plated and enamelled to protect the copper against the action of mercury. The protection is removed around the circumference and a small circle around the centre, and the exposed copper is amalgamated to facilitate the passage of current through the disc via the mercury. The interior surface of the mercury chamber is covered with insulation to prevent leakage of current.

A "C"-shaped permanent magnet *A* having pole-pieces *BB* passing through the upper and lower halves of the mercury chamber embraces the armature and provides the magnetic field for driving and

braking purposes. A metal band *C* lined with insulating material is clamped around the mercury chamber. A copper contact *J* passing through a bushed hole in the band forms one of the terminals to the mercury chamber; the other terminal consists of a copper wire, the exposed end of which is flush with the insulating lining and located between the lower pole-piece *B* and the centre of the mercury chamber. Both terminals are amalgamated on the surface which is in contact

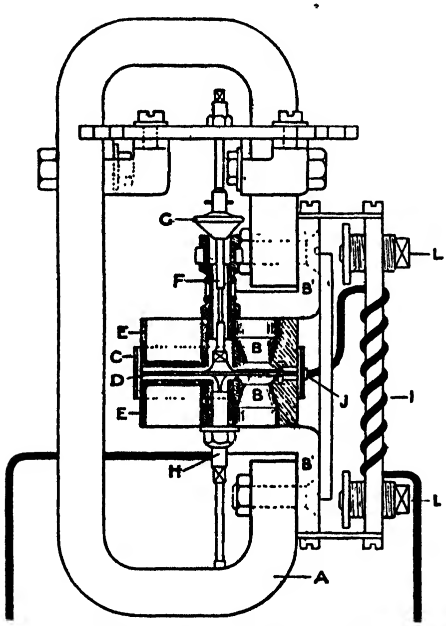


Fig. 8.—Chamberlain & Hookham direct-current A-H meter, general arrangement.

with the mercury, in order to reduce contact resistance. The position of the terminals is on a radial line which passes through the centre of the magnet poles, thus ensuring that the current passing from one terminal to the other through the copper disc, is concentrated between the magnet poles where it is most effective in producing driving torque.

The faces of the poles *BB* are covered with pole-caps consisting of a very thin layer of cupro-nickel, insulated from the poles and amalgamated on the side in contact with the mercury. These pole-caps lie in a direct line between the contacts, but owing to the extremely high resistance of the cupro-nickel alloy practically no current is

shunted from the armature. Although the cupro-nickel amalgamates readily with mercury, it does not dissolve appreciably and consequently the mercury is not fouled by its presence over a period of time. The object of the amalgamated pole caps is to permit mercury to flow readily and without excessive friction through the small gaps which separate the poles from the armature and to prevent air bubbles gaining access to these narrow spaces after the meter has been tilted or laid on its back during transport or storage. The bottom pivot of the rotor rests on a sapphire cup set in the jewel screw *H* and the latter can be removed for examination or exchanged if necessary.

An iron bar mounted adjacent to the pole pieces but separated therefrom by non-magnetic supports forms a magnetic shunt for the main flux crossing the magnet gap. The extremities of the bar are fitted with iron adjusting screws *LL* whereby the amount of magnetic flux shunted from the gap can be varied. Surrounding the bar is a correction coil *I*, one end of which is connected to the contact *J* and the other end to the negative terminal of the meter: the object of this coil is to compensate for the effects of fluid friction at high loads, as described earlier in this chapter. When no current is passing through the meter, a small proportion of the flux due to the permanent magnet *A* is shunted through the iron bar, the main portion passing across the gap between the poles *BB*. The direction of the winding on the correction coil is such that when current is passed through the meter, the amount of flux diverted through the bar is increased and that passing between the poles *BB* is reduced, the reduction being proportional to the current.

The driving force exerted by the armature due to the passage of current varies in direct proportion to the strength of the magnetic field in which it is operating, but the braking force exerted on the armature varies as the square of the strength of the field. The effect of a reduction in the main flux due to an increase in current is to reduce the ratio of driving force to current, but the ratio of braking force to current is reduced at a greater rate and consequently the speed of the armature tends to increase at a greater rate than the rate of increase in current. By suitably proportioning the ampere-turns on the correction coil *I*, the tendency for the meter to register slow on high loads due to fluid friction can be overcome. The effect of the correction coil on a Chamberlain and Hookham meter differs from that on a Ferranti meter; in the former the correction coil weakens the driving field, and in the latter the driving field is strengthened.

A register reading in kilowatt-hours at the declared voltage for which the meter is intended is driven by a pinion fitted on the upper end of the armature spindle *F*. A selection of change wheels is employed enabling a suitable gear ratio to be fitted when calibrating the meter. Any slight adjustment in armature speed which may subsequently be necessary can be easily accomplished by movement of the screws *LL* in the magnetic shunt.

2.11. Measurement Ltd. Direct Current Ampere-Hour Meter. The mercury motor meters described in the preceding paragraphs were developed forty years or more ago and although minor modifications in construction have been introduced from time to time, these meters still retain most of their original features. This fact is a great tribute to their inventors and it is not at all unusual to find a meter of this type which after twenty years or more in service without any attention still conforms closely to its initial calibration. No other class of direct current motor-meter can approach such a record of good performance. Judged by more recent designs however, these meters are comparatively large and heavy, and taking advantage of improvements in alloy steels for permanent magnets, it has been possible to produce mercury motor meters which are smaller and lighter. Generally, these more recent designs operate at a lower full-load speed with the result that no correction coil is necessary in order to maintain the usual limits of error at high loads. On the other hand a high-speed meter usually has a better performance at low loads.

The Measurement mercury motor ampere-hour meter, type H.M., is an example of a comparatively recent design and a sectional view of the meter element is shown in Fig. 9. The mercury chamber consists of a steel ring *R*, suitably varnished where it comes in contact with mercury, and secured between top and bottom plates *N*1 and *N*2 respectively. A bar magnet *M* of cobalt steel is secured to the bottom plate, across the diameter of the steel ring which forms part of the magnetic circuit. A shallow copper bell *D* mounted on a vertical spindle *Y* rests on a sapphire jewel and forms the rotating element of the meter. The rotor is immersed in mercury contained within the chamber and naturally tends to float; this tendency is counteracted by a balance weight *W* secured to the upper portion of the spindle, the weight being so proportioned that the rotor just sinks, thus imposing a very small weight on the bottom pivot and jewel.

In the lower plate *N*2 there are situated two insulating bushes *B*1 and *B*2 diametrically opposite each other and lying on the centre

line of the bar magnet. Two copper terminals $Z1$ and $Z2$ pass through these bushes and conduct the current into and out of the rotor via the mercury. In the top plate $N1$ immediately above these terminals are riveted two copper contacts $C1$ and $C2$. The function of these contacts is to concentrate the current in that portion of the rim of the rotor immediately adjacent to the magnet poles and to cause the current

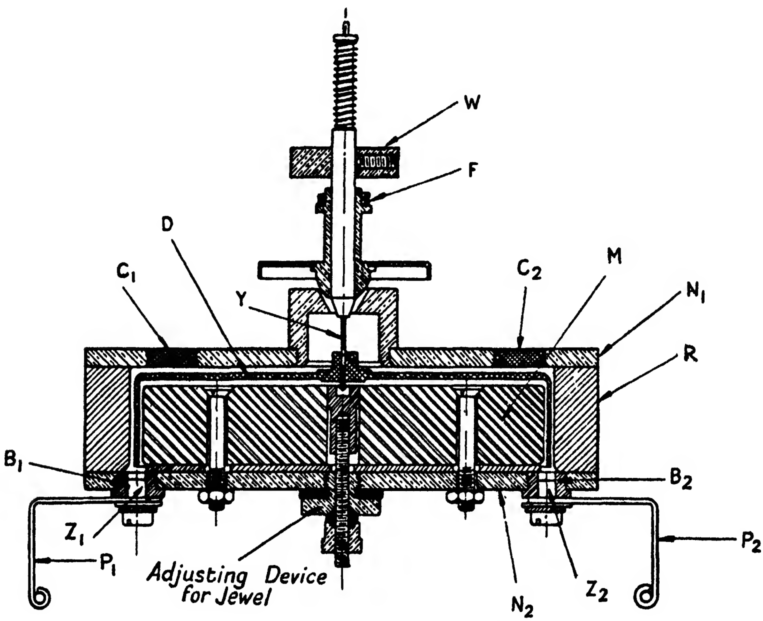


FIG. 9.—Measurement direct-current A-H meter, sectional view.

to travel vertically through the flux in the magnetic gaps. The path of the current through the element is from the terminal $P1$ to the contact $Z1$, vertically upwards through the rim of the rotor to the top plate contact $C1$, across the top plate to the other contact $C2$, vertically downwards through the rotor to the contact $Z2$, and out by terminal $P2$; the conducting path between the rotor and the contacts is of course bridged by the mercury in which the rotor is immersed.

It will be noted that the portions of the rotor in which the current density is the greatest are opposite the magnet poles where they are most effective in producing driving torque. In revolving through the magnetic field, eddy currents are induced in the rotor which react

with the field to produce a powerful magnetic brake. This results in a low rotational speed at full load and because fluid friction is thereby kept to a low value the curve at high loads remains reasonably flat without the necessity for a correction coil. The calibration of the meter is effected by means of an adjustable shunt connected across the terminals *P*1 and *P*2. The sealing of the mercury chamber for transportation is by means of a sliding sleeve *F* on the rotor shaft; the lower end of the sleeve is conical and can engage a conical recess in the upper portion of the top plate. Movement of the seal is controlled by a lever which is accessible from the terminal compartment when the terminal cover is removed.

2.12. Ampere-Hour Battery Meters. In addition to the more usual function of an ampere-hour meter of measuring the consumption in domestic and industrial installations, this type of meter is also used for determining the efficiency of accumulator batteries and for controlling their charge and discharge. For this class of duty the register reads in terms of "ampere-hours" instead of "kilowatt-hours" at some assumed voltage.

The efficiency of a battery of accumulators under operating conditions is determined by keeping a record of the ampere-hours input during charge and the ampere-hours output during discharge, over a succession of charges and discharges. Accumulator batteries of the stationary type are commonly used in generating stations and as the current values are usually substantial, shunted meters are employed. A common practice is to install one shunt across which are connected two meters, one to register the total ampere-hours charging current and the other the total ampere-hours discharge current. Both meters are fitted with a ratchet and pawl device which permits the rotor to move in one direction only and prevents reverse rotation. The connections to one of the meters are reversed with the result that when the battery is on charge, one meter runs in the forward direction while the other is tending to run backwards but cannot do so as it is restrained by the ratchet and pawl. When the battery is on discharge the second meter runs in the forward direction while the first tends to run backwards. By observing the meter readings at appropriate intervals, the battery attendant is enabled to maintain the battery in proper condition and any deterioration in efficiency after a lapse of time can be detected.

In an alternative arrangement a single meter is used. The rotor of the meter moves in the forward direction when the battery is on charge

and in the reverse direction on discharge. Two registers are provided, one to record the charge and the other the discharge. The gearing between the rotor and the registers may incorporate a differential gear in which an arbor driven by the rotor carries a planet wheel. Two sun wheels engaging with the planet are fitted with ratchets and pawls so that with the planet driven in one direction one sun wheel is driven and the other is locked by its pawl; when the planet is driven in the reverse direction the second sun wheel is driven and the first is locked. Each sun wheel drives on to its own register and in this manner a record of the ampere-hours expended in charge and discharge can be separated.

In this type of meter it is essential that with any particular load the speed of the rotor shall be the same whether moving in the forward or the backward direction. In these circumstances it is not possible to employ a meter fitted with a correction coil, since the effect of running such a meter backwards is to accentuate the error due to fluid friction instead of correcting the error. This is usually accomplished by the use of a slow-speed meter in which a powerful magnetic brake is incorporated, thus rendering the correction coil unnecessary.

2.13. Automatic Battery-Control Meters. A special type of battery meter made by Chamberlain & Hookham Ltd. is used in connection with stationary batteries such as are installed in automatic telephone exchanges in country districts. In these it is necessary for the batteries to be charged automatically without any attention other than an occasional visit from a maintenance engineer. A single meter is employed of the type which runs at the same speed in both directions; it is fitted with a register having a large diameter dial and a single pointer which makes excursions forwards and backwards, to and from a zero position. When the battery is fully charged the pointer stands at the zero position; as discharge takes place the pointer moves away from zero and when the battery is discharged the pointer will be in alignment with a red index which is adjustable by hand to a position on the scale corresponding to the capacity of the battery in ampere-hours. Thus, a glance at the pointer at any time will indicate how many ampere-hours have been discharged and how many still remain unused.

It is not customary to allow the battery to be completely discharged and automatic devices actuated by contacts incorporated in the register are used to recharge the battery at suitable intervals. A contact device is set to close when about 15 per cent. of the battery capacity has been discharged; the closure of this contact actuates a relay which switches

on the charging current either from a generator or a rectifier. When the charge is completed, the pointer will have travelled back to zero, at which point another contact is closed actuating a relay to switch off the charging current. If, during discharge, the charging device does not come into operation at the appropriate time the discharge will continue until the pointer has reached some other position on the scale, say at 40 per cent. discharge, where a warning light is switched on giving a visual indication that the battery requires attention. Should this warning not be observed and the discharge still continues the pointer will travel along the scale until a point is reached, say at 80 per cent. discharge, where another contact is closed giving a final warning at some distant point indicating a state of emergency. This final warning may be at a neighbouring exchange where a maintenance staff is located and from which immediate attention can be given. It will be appreciated that the contact devices can be utilized in conjunction with relays to fulfil a variety of functions according to requirements.

An important feature embodied in the automatic battery-control meter just described is the means for compensating for battery inefficiency. The ampere-hour efficiency of a lead/sulphuric acid battery of the Planté type is of the order of 90 per cent. If a battery in good condition is fully charged and 100 ampere-hours are used in the process, then 90 ampere-hours can be discharged from the battery before it reaches its original condition. It is necessary therefore when controlling the charge and discharge of a battery by automatic devices to make due allowance for the loss which takes place.

In the meter just described the speed of the rotor at any particular load is the same irrespective of the direction of rotation, that is, whether on charge or discharge. The large pointer on the register, however, travels more slowly in the charge direction than in the discharge direction with the same current, and this differentiation is achieved by a special form of gearing which gives one gear ratio when driven forward and another gear ratio when driven backward. The gearing is so arranged that the pointer indicates the ampere-hour capacity available in the battery for discharge and consequently the meter registers true ampere-hours on discharge. Thus, starting from zero reading, a charge of 110 ampere-hours will advance the pointer to a reading of 100 ampere-hours, which is the amount then available in the battery.

The dual gear ratio incorporated in the register is obtained by means of gearing as shown in Fig. 10. This gearing comprises two parallel

shafts A and B, A being driven by the meter and B being geared to the pointer. On shaft A, two pinions $C1$ and $D1$ are securely fixed and these engage with two wheels $C2$ and $D2$ on shaft B. The wheel $C2$ is coupled to shaft B through a friction clutch E which permits slip to take place under certain conditions. The wheel $D2$ is coupled to the shaft through a ratchet wheel F secured thereon, and a pawl G secured to $D2$ rests on F. The pinion $C1$ is larger than $D1$ and the wheel $C2$ is smaller than $D2$, consequently $C2$ always revolves faster than $D2$ irrespective of the direction in which they are driven.

When the meter is carrying current in the discharge direction, the shaft A will rotate in a clockwise direction as viewed from the right-hand end and as indicated by the arrow. Shaft B will rotate anticlock-

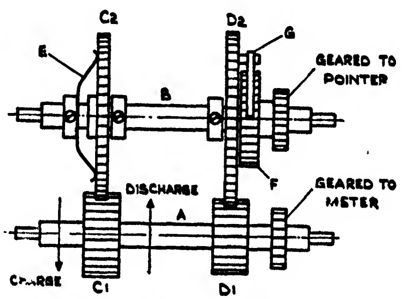


FIG. 10.—Chamberlain & Hookham battery-control meter, compensating gear.

wise together with the wheels $C2$ and $D2$, the latter being the slower of the pair. Under this condition shaft B together with the ratchet wheel F will be driven through the friction clutch E and the wheel $C2$. The wheel $D2$ which is revolving more slowly than $C2$ and consequently more slowly than ratchet wheel F will trail its pawl G backwards over the teeth of the ratchet wheel. The drive from the meter to the pointer will therefore be through the pair $C1$ and $C2$.

When the meter is carrying current in the charge direction, the shaft A will rotate in an anti-clockwise direction as viewed from the right-hand end and as indicated by the arrow. Shaft B will rotate clockwise together with the wheels $C2$ and $D2$. Under this condition shaft B together with ratchet wheel F will still be driven through friction clutch E and the wheel $C2$. The ratchet wheel is still tending to move faster than the wheel $D2$ but can no longer do so because it is now

driving against the pawl G, consequently F and $D2$ revolve in a clockwise direction at the same speed. Since ratchet wheel F is rigidly secured to shaft B, slip must now take place in the friction drive between E and $C2$, and the drive from the meter to the pointer will be through the pair $D1$ and $D2$. Thus the rate at which the pointer is driven by the meter in the discharge direction is determined by the gear ratio of $C1/C2$ and in the charge direction by the gear ratio of $D1/D2$. The ratio $C1/C2$ is always greater than $D1/D2$ and by a selection of suitable gears any difference between charge and discharge of from 10 per cent. to 30 per cent. can be arranged. The spring tension on E is adjusted so that the friction existing at this point is slightly in excess of that which is due to the pawl G slipping or trailing backwards over the teeth of the ratchet wheel F.

2.14. Electric Vehicle Meters. An ampere-hour meter similar in construction to the foregoing is used for taking care of the battery on electric vehicles and locomotives; in this case the working conditions are different and it is usual to incorporate one contact maker only. The battery receives its charge at a garage or some other central point, usually from a generator or through a rectifier. When fully charged a contact-maker at the zero position on the scale is closed thus actuating a relay for switching off the charging current. The vehicle may then be taken out on the road and the position of the pointer on the scale serves as an indication to the driver, of the charge available in the battery. A red index which is adjustable indicates the point beyond which it is unwise to discharge the battery. Thus the meter fulfils the same function as the petrol gauge in a motor-car.

The working conditions to which a vehicle battery is subjected are much more severe than in the case of a stationary battery. At starting, the discharge is very heavy for a short interval and on steep ascents a heavy discharge may be maintained for several minutes. For this service it is usual to rate the meter to carry 300 per cent. load for five minutes and a much heavier load for a shorter period. Because of the severe operating conditions, the efficiency of the battery is lower and the usual allowance for the difference between charge and discharge ampere-hours is 14 or 15 per cent. in the case of a lead battery and 25 to 30 per cent. in the case of a nickel-iron (Edison) battery.

2.15. Electro-Deposition Meters. An ampere-hour meter similar to the electric vehicle meter is used for controlling the deposition of metal in electrolytic processes and plating vats. According to Faraday's laws of electrolysis the amount of each element deposited by unit quantity

of electricity is a definite and constant quantity which is termed the electro-chemical equivalent of the metal deposited. If the same quantity of electricity be passed through different electrolytes the weights of the separated elements will be proportional to their chemical equivalents. These laws may be expressed by the formula $W = I \times e \times t$ where

W = weight in grams
I = current in amperes
e = electro-chemical equivalent.
t = time in seconds.

The theoretical weight of various metals deposited per ampere-hour from various solutions is as follows:

Gold (chloride)	2·45 grams per ampere-hour.
Gold (cyanide)	7·35 ,, ,, ,,
Silver	4·02 ,, ,, ,,
Platinum	1·82 ,, ,, ,,
Cadmium	2·09 ,, ,, ,,
Copper (sulphate)	1·18 ,, ,, ,,
Copper (cyanide)	2·36 ,, ,, ,,

In electroplating operations, particularly in the deposition of the metals gold, silver, platinum and the like, it is sometimes necessary to determine the weight of metal to be deposited on an article or a number of articles. An ampere-hour meter can be used for this purpose and the register is scaled in terms of pennyweights or grams of gold, silver or whatever the metal may be. A pointer which is friction-tight on its arbor is set manually to any desired point on the scale corresponding to the weight of metal to be deposited and the current is switched on to the plating vat. As the operation proceeds the pointer travels back towards zero and on reaching this point a contact is closed which actuates a relay to switch off the current to the vat. This meter, unlike the battery meters previously referred to, operates in one direction only.

It may be noted that the figures giving the theoretical weight of metal deposited per ampere-hour represent an efficiency of 100 per cent.; in practice this efficiency is not attained and in fact the actual value varies widely. It is necessary therefore to know the efficiency of the vat in which the operation is performed, but knowing this, the meter reading can be adjusted accordingly. A further point to note is that the weight of deposit per ampere-hour depends in some cases on the solution employed. For example, in the case of copper, twice the

weight of deposit is obtained from a cyanide solution as from a sulphate solution and in the case of gold, three times the weight is obtained from a cyanide solution as from a chloride solution. For further information on this subject, a handbook on electro-deposition such as Canning's *Manual for Electroplaters* should be consulted.

2.16. Direct-Current Watt-Hour Meters. Although ampere-hour meters have been used so extensively for measuring the quantity of direct-current electrical energy supplied to domestic consumers, the accuracy of the measurement is based on the assumption that the voltage of the supply is maintained at the declared value for which the meter has been calibrated. This assumption cannot always be accepted and in cases where it is known that the voltage is subject to variation outside the accepted limits, the use of a watt-hour meter is essential. In this country the use of direct-current watt-hour meters is confined mainly to generating stations and substations, traction systems and large industrial supplies.

One of the earliest forms of watt-hour meter was the Elihu Thomson meter, which is of the dynamometer type. It consists of a motor having a wound armature and a commutator, free to revolve on a vertical spindle, and connected in series with a high resistance across the supply mains. The current in the main circuit passes through two field coils connected in series, and arranged one on each side of the armature; the armature and field coils contain no iron in their magnetic circuits. A brake disc mounted on the armature shaft is embraced by one or more permanent magnets in order to reduce the speed of rotation and to adjust this to the desired value, and these magnets are screened so that they exert a negligible influence on the driving fields of the meter. This type of meter has never been popular in this country and like all commutator meters it cannot be regarded as a reliable instrument.

The Aron clock meter which is a direct-current watt-hour meter, is also of the dynamometer type, and both theoretically and practically is a much more accurate instrument; it has been used extensively in the past and is capable of giving a good performance. It is relatively costly and its maintenance requires the services of mechanics highly skilled in clock construction and repair; for these reasons and because of the restricted market for direct-current meters it is now manufactured in this country only on a very small scale.

The mercury-motor direct-current watt-hour meter is made by several firms in this country. The various constructions are based

largely on the fundamental principles embodied in Hookham's original mercury-motor ampere-hour meter but with an electromagnet taking the place of the permanent magnet for providing the driving field. Generally the performance of mercury-motor watt-hour meters on varying voltage is not as good as in dynamometer meters, but they have other compensating advantages and their maintenance can be handled efficiently by meter mechanics accustomed to the overhaul of mercury motor ampere-hour meters.

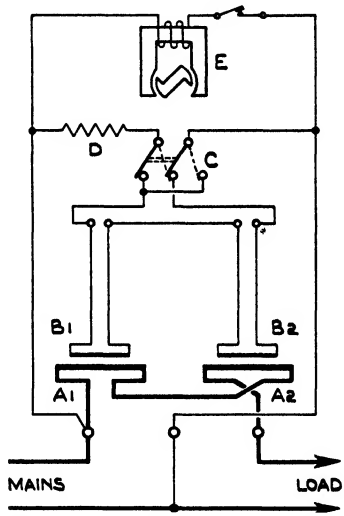


FIG. 11.—Aron pendulum watt-hour meter, internal connections.

2.17. Aron Pendulum Watt-Hour Meter. The Aron direct-current watt-hour meter consists essentially of an electrically-wound clock having two pendulums swinging nearly in synchronism when no current is passing through the main circuit of the meter. Each pendulum at its lower extremity carries a fine wire coil energized by the supply voltage and swings immediately above a coil energized by the current in the main circuit. The connections to the coils are so arranged that when current flows in the main circuit the rate of swing of one pendulum is accelerated and the other retarded; the difference between the rates of swing is a measure of the power in the circuit and this, integrated over a period, is equal to the energy consumption.

The arrangement of the electrical connections is shown diagrammatically in Fig. 11. Two current coils $A1$ and $A2$ are connected in series across the main terminals of the meter; the polarity is such that one presents a north pole and the other a south pole at the uppermost end. Two voltage coils $B1$ and $B2$ attached to the lower extremities of two pendulums are connected in series and at any given instant the polarity of one is the same as that of the other. These voltage coils are connected across the supply mains in series with a reversing switch C and a resistance D. A winding-motor E is also connected across the mains and is energized intermittently at regular intervals by the momentary closure of an automatic switch in series with the field winding. The function of the winding-motor E is to maintain tension in a spring which provides the power for driving the pendulums; the spring is rewound every half-minute by the armature of the motor moving through an angle of about 75 deg. The circuit through the field winding is normally open, but when the spring is run down a " tip-over " switch closes the circuit, energizing the field magnet and restoring the armature to the position in which the spring is fully wound. The action is practically instantaneous and on completion of the winding movement the switch is re-opened.

The system of clockwork mechanism incorporated in the Aron meter appears to be very complicated, but this is largely due to the inclusion of various devices intended to correct errors arising from inevitable mechanical imperfections. Stripped of these refinements and reduced to its simplest form, the gearing is comparatively simple and is shown diagrammatically in Fig. 12. The winding-motor E maintains at all times sufficient driving power in a spring A to keep the two pendulums $B1$ and $B2$ swinging constantly. The power is transmitted through a differential gear consisting of a planet wheel C engaging with two sun wheels $D1$ and $D2$. The planet wheel is free to revolve on an arm fixed to, and projecting at right-angles from, the shaft F. The sun wheels are free to revolve independently on this shaft which is constantly impelled in the direction of the arrow on the winding-motor. The sun wheel $D1$ drives through gearing on to the shaft $G1$ carrying the escapement wheel $H1$, and similarly the sun wheel $D2$ drives through gearing on to the shaft $G2$ carrying the escapement wheel $H2$. The arrows on the wheels indicate the direction of movement and it will be noted that owing to the inclusion of an extra pinion in one gear train the two shafts revolve in opposite directions. Two pairs of pallet arms $J1$ and $J2$ attached to the rods of the

pendulums $B1$ and $B2$ engage with the escapement wheels $H1$ and $H2$. If the pendulums swing at the same rate, the shafts $G1$ and $G2$ will also revolve at the same speed and likewise the sun wheels $D1$ and $D2$.

Under this condition the planet wheel C will be carried round on its arm in the same direction as the sun wheels, but without revolving on its own axis. If however, one pendulum swings faster than the other, its associated sun wheel will also turn faster and the planet wheel will

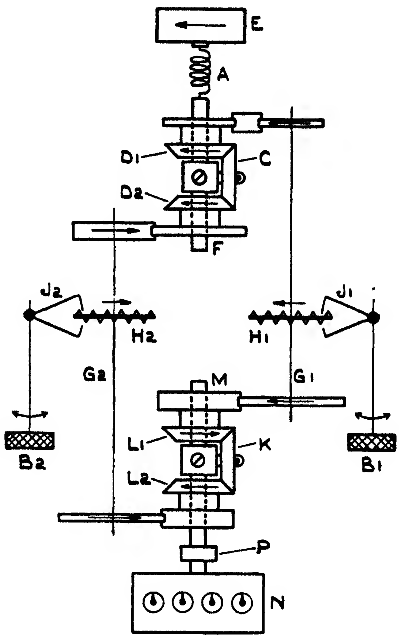


FIG. 12.—Aron pendulum watt-hour meter, diagrammatic arrangement of gearing.

then revolve on its own axis in addition to revolving around the shaft F. A second differential gear comprising a planet wheel K and sun wheels $L1$ and $L2$ mounted on a shaft M is driven by the shafts $G1$ and $G2$. Unlike the first differential the sun wheels in the second are driven in opposite directions and if the opposing speeds are equal the planet wheel K will merely revolve on its own axis without communicating any motion to the shaft M. On the other hand, if the opposing speeds are unequal as is the case if one pendulum swings faster than the other, the planet wheel will cause the shaft M to revolve, and a register N

driven by the shaft will indicate the total number of revolutions in appropriate units.

It is now possible to follow the method of operation of the Aron meter. Assuming that the voltage circuits of the meter are energized and that the pendulums are adjusted to swing in synchronism when no current is passing through the current coils, the shafts *G*1 and *G*2 driven by the power derived from the winding motor *E* and transmitted through the first differential will revolve in opposite directions at equal speeds. The sun wheels of the second differential will likewise revolve in opposite directions at equal speeds, turning the planet wheel *K* on its own axis but communicating no motion to the shaft *M*, under this condition no registration will take place on the dials of the register *N*. If, now, current is passed through the current coils of the meter, one pendulum will be accelerated and the other retarded, thus altering the speeds of the shafts *G*1 and *G*2. These in turn will cause corresponding changes in the speeds of the sun wheels *L*1 and *L*2 with the result that the planet wheel *K* will roll round the slower moving sun wheel, driving the shaft *M* in the same direction. The speed of the shaft *M* will correspond to the power in watts passing through the meter and over a period of time the register will show the consumption in kilowatt-hours.

The foregoing description applies to the meter in its elementary form, but in practice it is found impossible to obtain synchronous swinging of the pendulums on no-load for a prolonged period owing to variable friction in the gear trains. This causes one pendulum to accelerate and the other to slow down and consequently results in a positive or a negative reading on the register in course of time, without any load on the consumer's circuit. In order to avoid this possibility, a reversing switch is introduced as shown at *C* in Fig. 11, and a reversing gear is introduced between the second differential shaft *M* and the register *N* at the point *P* in Fig. 12. Both these components are actuated from the first differential shaft *F* and reversal of both is effected simultaneously at intervals of 10 minutes. Thus, any false registration due to friction affecting one pendulum would cancel out over a twenty-minute interval and the maximum error at any time due to this cause could not exceed ten minutes' duration.

The effect produced by the reversing switch is to reverse the polarity of the pendulum coils with the result that under load conditions the pendulum which was swinging the faster becomes the slower and the direction of rotation of the second differential shaft *M* is reversed.

Since the reversing gear between the differential and the register changes over at the same instant the register continues to record current consumption in the forward direction. It will be obvious from the foregoing that the Aron pendulum meter will commence to register with the smallest current through the current coils, and since there is no iron in the current or voltage electromagnets the meter should have a substantially straight-line law throughout its range of measurement.

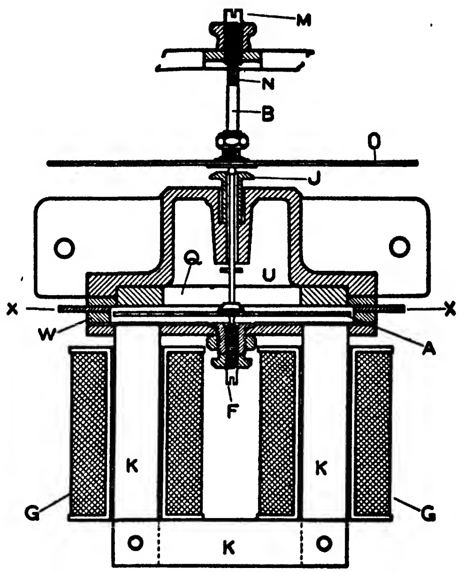


FIG. 13.—Chamberlain & Hookham direct-current watt-hour meter, sectional view.

2.18. Chamberlain and Hookham Mercury Motor Watt-Hour Meter. The Chamberlain and Hookham direct-current watt-hour meter is of the mercury-motor type and incorporates the fundamental principles embodied in Hookham's original mercury motor ampere-hour meter. It differs from the latter in that the main driving field is provided by an electromagnet instead of a permanent magnet and the braking field is provided by a separate brake magnet. Fig. 13 shows a sectional view of the driving element of this meter. An amalgamated copper disc *A* mounted on a vertical spindle *B* forms the rotor and the disc is immersed in mercury. An aluminium brake disc *O* mounted on the upper part of the spindle, rotates between the poles of a permanent magnet (not

shown). The core of a "U"-shaped electromagnet *K* built up with soft iron laminations, is attached to the bottom portion of the mercury chamber.

Voltage coils *GG* having many turns of fine wire wound on both limbs of the core are connected across the supply mains, and set up a magnetic field which cuts vertically through the copper disc *A*. An iron ring *Q*, fitted in the top of the mercury chamber above the disc, completes the magnetic circuit. A ring of insulating material *W* surrounding the mercury chamber, has two contacts *XX* at diametrically opposite points and in line with the poles of the electromagnet *K*. Current from the positive supply main enters at the left-hand contact *X* and after passing through the disc, via the mercury, leaves by the right-hand contact; it then passes through a correction coil (not shown) consisting of a few turns of heavy gauge wire wound around the upper ends of the core *K* and thence to the positive load terminal of the meter.

It will be noted that the current carried by the disc cuts twice through the magnetic field created by the voltage electromagnet, thus increasing the driving torque exerted by the rotor. The copper disc has a number of radial slits around its circumference with the object of reducing eddy currents induced therein by its movement through the magnetic field of the voltage electromagnet; another object of the slits is to confine the current as much as possible to that part of the disc which is in the strongest magnetic field, thus further increasing the driving torque. The rotor is supported on a cupped sapphire, mounted in a screw *F* in the bottom of the mercury chamber. The upper part of the chamber *U* is shaped like the well-known invertible inkwell to avoid spilling of the mercury during transit. A pinion *N* on the top of the rotor shaft *B* engages with a register (not shown) which records the kilowatt-hours passed through the circuit.

The driving force exerted by the rotor is proportional to the current passing through the copper disc and to the voltage applied to the voltage electromagnet. The speed of the rotor is proportional to the watts and is adjusted to a suitable value by means of the brake magnet. The characteristic curve of the meter is similar to that of a mercury motor ampere-hour meter as shown in Fig. 6 (page 23). At high loads the meter tends to run slow due to fluid friction between the copper disc and the mercury. As explained earlier in this chapter, fluid friction increases as the square of the speed of the disc and this tendency is rectified by the correction coil which augments the magnetic field set

up by the voltage electromagnet, thus increasing the driving torque. The smallest direct-current watt-hour meter made by Chamberlain and Hookham Ltd. is rated at ten amperes on full load. For larger current ratings a shunt is employed and so arranged that the meter carries ten amperes when rated full-load current is passed through the combination; thus it is possible in the case of meters with external shunts to disconnect the meter and carry out tests on the basis of ten amperes full-load current without having to disturb the shunt.

2.19. Shunts. A shunt is a resistor connected in parallel with a meter in order to reduce the amount of current passing through the meter current element. In some types of direct-current ampere-hour meter, as for example electrolytic and commutator types, the current through the measuring element is very small and the shunt may be regarded as carrying the whole of the current to be metered. In other types such as mercury-motor ampere-hour or watt-hour meter, practice varies with different makers and the meter current circuit may require from five to fifty amperes at full load, the remainder of the current in the main circuit being carried by the shunt. In a well-designed shunt the resistance value does not alter appreciably with change of temperature and in order to avoid errors in the meter due to thermo-electric effects in the shunt or the connecting leads, the temperature rise after continuous operation at maximum loading must be relatively small.

The main terminals of a shunt are usually constructed of cast brass or copper. If currents of the order of 100 amperes or more are passed through the shunt, the resistance material between the main terminals is preferably in the form of flat strips or plates in order to expose as large an area as possible to the cooling influence of the surrounding air. In many cases the resistance material employed for meter shunts is a cupro-nickel alloy such as Constantan although in some instances a cupro-manganese alloy with a small addition of nickel, such as Manganin or Tarnac is used. A typical cupro-nickel alloy is composed of 57 per cent. copper and 43 per cent. nickel, and has a resistivity approximately thirty times that of copper. It has a temperature coefficient of 0·000005 per cent. per deg. C. which may be regarded as negligible, and a thermo-e.m.f. against copper of 39 microvolts which is rather high. A typical cupro-manganese alloy is composed of 84 per cent. copper, 13 per cent. manganese, 2·5 per cent. nickel and a trace of iron. This has a resistivity approximately twenty-six times that of copper, a temperature coefficient of 0·000017 per cent. per deg. C. and a thermo-e.m.f. against copper of 4 microvolts, which is very low.

Although Constantan has a high thermo-e.m.f. as compared with Manganin it is preferred by many makers owing to the ease with which it can be soldered and because of its stability. Manganin on the other hand cannot be soft-soldered and in the case of large shunts a good joint between the Manganin and the brass or copper is not easy to obtain. Hard soldering or brazing must be resorted to and as Manganin oxydizes readily at brazing heat great care is necessary; also the resistance of the shunt has a tendency to change with time and does not become stable until some months after brazing.

2.20. Installation of Shunts. When a shunt is carrying current, heat is generated and certain precautions are necessary if the best results are to be obtained. In the case of a large shunt connected in a run of bus-bars, the shunt should be fixed horizontally, that is, so that the current passes in a horizontal direction. The plates of the shunt should lie in a vertical plane so that a current of air can circulate naturally between them; this assists in keeping the shunt cool. The joints between the bus-bars and the shunt should be clean and the bolts pulled up tightly, as a poor joint may result in excessive heating. A great deal of the heat developed in the shunt is conducted away by the bus-bars, and these often have a greater influence on the temperature rise than the design of the shunt itself. If owing to unavoidable circumstances it is necessary to erect a shunt in a vertical run, the bottom terminal should be made positive. Normally the upper terminal would tend to get hotter than the lower owing to the heat rising, but owing to the Peltier effect, this tendency may be partly or wholly neutralized.

2.21. Thermo-Electric Forces in Shunts. When current is passed through a shunt, heating takes place owing to the relatively high resistance between the shunt terminals. For a given voltage-drop across the shunt the amount of heat developed at maximum current will be a constant quantity. The temperature rise will therefore depend largely upon the area exposed to cool air surrounding the shunt and partly to the cooling effect of the bus-bars. By making a larger shunt, the temperature rise can be reduced but there is an economic limit to this procedure apart from limitations of space. According to the British Standard for Electricity Meters, B.S. 37: 1937, the maximum observable temperature rise of any part of an external shunt, above the temperature of the surrounding air, after carrying the marked current for two hours must not exceed 75 deg. C. This limitation is necessary in order to minimize inaccuracies in the meter due in part to thermo-electric effects. The most important of these are the Seebeck effect and the Peltier effect.

The Seebeck effect can be observed by connecting two copper wires to the terminals of a sensitive galvanometer; the free ends of the copper wires are connected to the ends of a piece of Constantan wire. If one of the copper-Constantan junctions is heated a deflection will be observed on the galvanometer, indicating the passage of current; if the other junction is heated a deflection will again be observed but in the opposite direction from the first.

The Peltier effect is the result of passing direct current through the two junctions of dissimilar metals in a shunt. At the positive end where current passes from copper or brass to Constantan an increase of temperature may be observed and at the negative end where the direction of current is from Constantan to copper or brass a reduction of temperature will be found. This effect is superimposed on the normal increase of temperature due to the passage of current through a resistance and results in the positive end becoming hotter than the negative end. The effect would not be observable if alternating current were used as each end would be alternatively positive and negative and the results would cancel out.

Consider now the effects produced on a direct-current meter connected to a shunt which is carrying a substantial load. Initially both ends of the shunt will be at the same temperature and no unusual effect will be observed on the meter. After sufficient time has elapsed for the shunt to attain its normal working temperature at the load in question it will be found that the positive end is hotter than the negative, due to the Peltier effect. At both ends of the shunt a thermo-junction exists, having a thermo-e.m.f. proportional to the temperature and these e.m.fs. are acting in opposite directions. Since the positive end of the shunt is the hotter, it will produce the greater e.m.f. and will cause a current to circulate through the meter current circuit in a direction to assist the main current. The magnitude of this current may be insufficient to affect appreciably the normal error of the meter, but if the load be reduced to a low value, say 5 per cent. of full load, there may be a noticeable difference in the error in which case the meter will be registering faster than before. If after the shunt has been carrying full load for a considerable period, the current in the main circuit is switched off, the circulating current may be sufficient to cause the meter to creep around in the forward direction. This is the Seebeck effect and a current will continue to circulate so long as the two ends of the shunt are at different temperatures. From the foregoing it will be appreciated that a poor joint at one end of the shunt, resulting in undue

heating, will have a similar effect. If excessive heating takes place at the positive end it will increase the current in the meter current circuit but if the heating is at the negative end it will reduce the meter current.

2.22. Compensation for Errors in Shunted Meters. The errors arising in meters due to thermo-electric effects in shunts can be largely eliminated by careful design of the leads connecting the meter to the shunt. It is usual for meters having external shunts to be provided with shunt leads several feet long in order that the meter may be located away from the shunt where it will be unaffected by heat or magnetic fields due to the passage of heavy currents. By making the ends of the shunt leads where they are attached to the shunt of the same metal as the shunt itself, i.e. Constantan or the like, and by attaching the leads at points close up to the joint between the end blocks of the shunt and the Constantan plates, a thermo-junction can be introduced into each shunt lead which will exert a thermo-e.m.f. substantially equal to and opposite from that set up in the shunt itself. These end-pieces, which are preferably of strip or wire, must be of sufficient length to ensure that the joints between the Constantan and the shunt leads are both at the same temperature because two additional thermo-junctions exist at these points and their e.m.fs. must also be equal and opposite.

Mercury-motor meters which are unshunted frequently have a large temperature error; this error is partly due to the increase in resistance with temperature of the copper armature disc. The torque of the meter does not vary much with change of temperature but the brake force exerted by the armature will vary inversely with its resistance; it follows therefore that an increase in temperature will cause the meter to run faster. If the meter is shunted and the shunt leads are made of copper, these also will increase in resistance with increase in temperature and the current in the meter current circuit will be correspondingly reduced. The effect of this reduction in current is to make the meter slower and thus to tend to compensate for the temperature error of the meter itself. The effect varies with different makes of meter, but generally it may be said that the larger the ratio of shunted current to meter current, the smaller will be the temperature error and that for meters of ratings above 300 amperes the temperature error is usually of negligible proportions.

CHAPTER III

SINGLE-PHASE METERS: CONSTRUCTIONAL DETAILS

3.1. Early Developments. The earliest attempts to arrive at the value of the supply of alternating current were made by means of a time meter. This consisted of a spring-driven clock which, when no current was being supplied, was prevented from working by an electromagnetic device. When current was being used, an electromagnet was energized and the escapement of the clock was released; this permitted the clock to drive a register, recording the time in hours during which current had passed. As the load in those days consisted mainly of arc lamps, the current consumption of which was known, a record of the hours of use was sufficient for most purposes.

The next variety of meter to be developed was an induction type ampere-hour motor meter invented by Shallenberger. This consisted of what was in effect a transformer having a short-circuited secondary winding. The primary winding which carried the current in the main circuit was arranged with its magnetic axis in a horizontal plane; the secondary, consisting of heavy section short-circuited turns, was fitted inside the primary; its axis, also in a horizontal plane, was displaced at an angle of about 45 deg. to the axis of the primary.

A light aluminium disc on which an iron ring was fitted was mounted on a vertical spindle and was free to rotate in the magnetic field created by the primary and secondary coils. The magnetic field due to the secondary coil was displaced both in phase and in space with respect to the primary field, and the interaction of these fields on the iron ring resulted in rotation of the disc and spindle. A light four-bladed fan was mounted on the lower end of the spindle and functioned as an air brake. The driving torque was proportional to the square of the current in the main circuit and the brake torque due to the fan rotating in air was proportional to the square of the speed. The resultant of the two opposing torques was a speed of rotor proportional to the current.

The torque developed in the rotor, judged by modern ideas, was very small and at one-fifth load was only one twenty-fifth of the full-load torque, since it followed a square law. As a result, the range over which any pretence to accuracy could be achieved was very restricted, in addition to which, inherent errors of considerable magnitude

existed. One source of error which no longer troubles the meter engineer was the state of the barometer. Since the density of the air in which the fan-brake revolved varied with barometric pressure, it was necessary to make allowance for this factor in calibrating the meter.

Following the Shallenberger meter came the Elihu Thomson commutator-motor meter and the Aron pendulum-clock meter, both of which have already been described in the previous chapter. Both these types are watt-hour meters and can be used for alternating-current measurements although their greatest field of usefulness has been in connection with direct-current work. They appeared about the same time as the Blathy meter which was an induction-type alternating-current watt-hour meter. The advantages of induction-type watt-hour meters

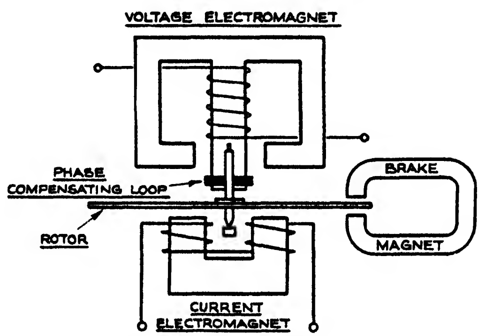


FIG. 14.—Single-phase meter elements, diagrammatic arrangement.

were soon appreciated, in particular the absence of commutator and brushes, and the lightness and simplicity of the moving element. The early productions were accurate on non-inductive loads only and had errors which increased as the power factor of the load decreased; many means were adopted for overcoming this disadvantage which assumed greater importance with the increased use of electricity for power purposes. The present method of applying the necessary correction for inductive loads was due to Tesla, whose patents prevented full use being made of a very simple solution. With the lapse of these patents great strides were made in the design and development of induction meters, which to-day have reached a high degree of perfection.

3.2. Elements of Single-Phase Meter. The outstanding feature of a single-phase induction-type meter is its simplicity. The essential parts

are shown diagrammatically in Fig. 14, these comprise a voltage electromagnet, a current electromagnet, a brake magnet and a rotor. The voltage electromagnet consists of a number of m-shaped iron laminations assembled together to form a core. On the middle limb of the core a coil is fitted having a large number of turns of fine wire; this coil is connected across the supply mains. The two outer limbs of the core at their extremities turn inwards and nearly join up to the middle limb. The narrow airgaps between the outer and middle limbs introduce considerable reluctance in the magnetic circuit and result in a leakage field which cuts through the rotor and forms part of the main driving flux of the meter. In some makes of meter the middle limb projects downwards a short distance beyond the outer limbs and the driving flux is concentrated in the area around the extremity of this limb.

The current electromagnet consists of a number of ⊔-shaped iron laminations assembled together to form a core. Each of the two limbs is wound with a few turns of heavy-gauge wire which are connected in one of the lines and in series with the load to be metered; when current is passing around the main circuit the current electromagnet is energized and the magnetic field set up cuts through the rotor. The rotor consists of an aluminium disc mounted on a vertical spindle and supported on a sapphire cup contained in a bottom bearing screw. The bottom pivot, which is usually removable is of hardened steel, and the end, which is hemispherical in shape, rests in the sapphire cup. The top pivot merely serves to maintain the spindle in a vertical position under working conditions and does not support any weight or exert appreciable thrust in any direction.

The magnetic field of the voltage electromagnet which is pulsating in character cuts through the rotor and sets up eddy currents therein, but normally does not of itself produce any driving force. The magnetic field of the current electromagnet also sets up eddy currents in the rotor but similarly does not in itself produce any driving force. In a single-phase meter carrying a non-inductive load there is a phase displacement of 90 deg. between the magnetic fields arising from the voltage and current electromagnets. The reaction between these magnetic fields and eddy currents sets up a driving force or torque in the rotor which, in the absence of any opposing force would revolve at a very high speed.

The brake magnet consists of a more or less C-shaped piece of alloy steel bent round to form a complete magnetic circuit, with the exception of a narrow gap between the poles; the magnet is mounted

so that the rotor revolves in the airgap between the polar extremities. The movement of the rotor through the magnetic field crossing the airgap sets up eddy currents in the rotor which react with the field and exert a braking effect. By altering the position of the brake magnet or by diverting some of the flux therefrom, the speed of the rotor may be adjusted. In some makes of meter, two magnets are provided in order to obtain a greater braking effort.

The foregoing brief description of a single-phase meter element applies to the majority of makes now available. In the past a great deal of ingenuity has been expended in devising variations in the shape of the voltage and current electromagnets. Some manufacturers have made the voltage electromagnet bi-polar and the current electromagnet tri-polar, others have made the voltage electromagnet with bifurcated or trifurcated polar extremities in the slots of which, the current windings have been placed. Doubtless the manufacturers of such, consider that some constructional advantage from the point of view of compactness or convenience in manufacture results from their choice of form, but from the point of view of performance, little if any advantage can be claimed.

3.3. Full-load Adjustment. The full-load adjustment of an induction meter is almost invariably made by means of a device operating on the brake magnet or magnets. Attempts have been made in the past to control the speed of the rotor by an alteration in the position of the current electromagnet. The effect of this has been to increase or decrease the driving torque, leaving the braking system unaltered. This method has the disadvantage that any movement of the current electromagnet usually has a disturbing effect on the low-load and inductive-load adjustments, thus necessitating a check and possible readjustment at other points on the curve: an adjustment of the brake magnet can be made to be quite independent of any other adjustments which may be necessary. Although referred to somewhat loosely as "full-load adjustment", this device is effective in controlling the speed of the rotor at any load from the maximum down to 25 per cent. of rated full load. Below this point the low-load adjustment can modify the effect of the main adjustment as may be desired and with increasing influence as the load becomes less. It is usual in a manufacturer's test-room, when calibrating a meter for the first time, to set the inductive-load and low-load adjustments prior to making the full-load adjustment. If these initial settings are skilfully carried out, it should only be necessary, after making the full-load adjustment, to verify

the accuracy of the meter on one inductive load, and one or more low-load points, to ensure that the meter errors lie within the prescribed limits.

The brake magnet of a meter is one of its most important components since the sustained accuracy of the meter is mainly dependent upon the constancy of the flux which this magnet provides. The design of the brake magnet system has received a great deal of attention from meter engineers both from the point of view of stability of flux and convenience of adjustment. Considerable improvements have been

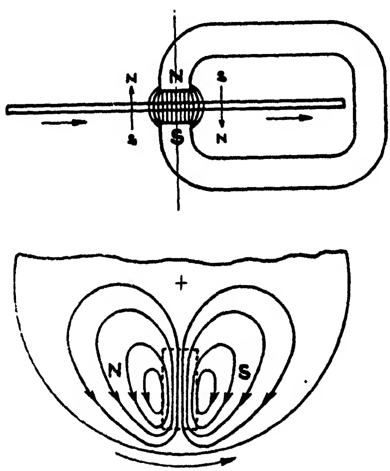


FIG. 15.—Path of induced currents in meter brake-disc.

made in permanent magnet alloys during recent years. The alloys commonly employed in the manufacture of permanent magnets for alternating-current meters are tungsten or chrome steel, cobalt steel, nickel-aluminium steel or nickel-aluminium-cobalt steel.

When a metal disc is rotated between the poles of a permanent magnet, an e.m.f. is induced in the disc in the area between the magnet poles and at right angles to the direction of rotation. This e.m.f. causes eddy currents to circulate in the disc, the magnitude of which are directly proportional to the flux emanating from the magnet poles and to the rate at which the flux is cut by the disc; their value is inversely proportional to the resistance of the path in which they flow. The effect of these eddy currents reacting on the magnetic field of the

brake-magnet is to set up a retarding force tending to oppose rotation and directly proportional to the speed at which the disc rotates.

In Fig. 15 is shown a disc rotating between the poles of a brake magnet in an anti-clockwise direction as viewed from above. The magnet has a north pole above the disc and in the plan view, the path of the induced currents is shown; the position of the magnet pole relative to the circumference of the disc is indicated by a rectangular space and the induced e.m.f. acts in a radial direction, setting up currents in the disc in directions as indicated by the arrows. The magnetic field set up by these induced currents results in a north pole above the disc in the area approaching the north pole of the brake magnet and a south pole in the receding area; below the disc these polarities are of opposite sign. It will be noted that the approaching poles result in repulsion and the receding poles in attraction and the forces are directly proportional to the speed at which the disc rotates. Movement of the brake magnet poles towards the centre of the disc by means of an adjusting device, will increase the speed of the rotor at any given load. In Fig. 16 a braking system built up with two magnets is shown; the magnets are magnetized in opposite directions and when assembled, set up magnetic fields which cut through the disc in opposite directions. The e.m.fs. induced by the rotation of the disc in an anti-clockwise direction, as viewed from above, result in eddy currents as indicated by the arrows. Three magnetic fields result from these eddy currents, the effect of which is the same as in the previous example. The polarity of the field set up in the disc in the space between the two magnets results in attraction between that portion of the disc leaving the left-hand magnet and repulsion as it approaches the right-hand magnet.

In a modern single-phase meter the speed of the rotor at rated full load usually lies between twenty and thirty revolutions per minute. Other things being equal, the lower the speed, the better will be the overall performance of the meter: a low speed can only be achieved by the use of a relatively powerful braking system involving a single magnet or a pair of magnets. The advantage of a single magnet is that it occupies but a small space where space may be valuable for other purposes and it is considerably lighter in weight than the dual-magnet system. On the other hand the adjustment of the brake force may involve the movement of the magnet either by swivelling or by sliding along the surface of a supporting bracket, although at least one manufacturer has devised means of varying the brake force without moving the magnet. The cost of the single magnet may equal or even exceed

the cost of two magnets, since high-grade alloy steel, which is expensive, is usually required for the former, whereas lower-grade steel may provide sufficient brake force if two magnets are employed. The advantage of a dual magnet system is that the magnets may be fixed in position and adjustment of the brake force may be made by means of an adjustable magnetic shunt which is very easy to operate: some manufacturers who employ the dual-magnet system sacrifice this advantage by making the magnets adjustable for position.

An important feature in the design of a brake magnet is the shape

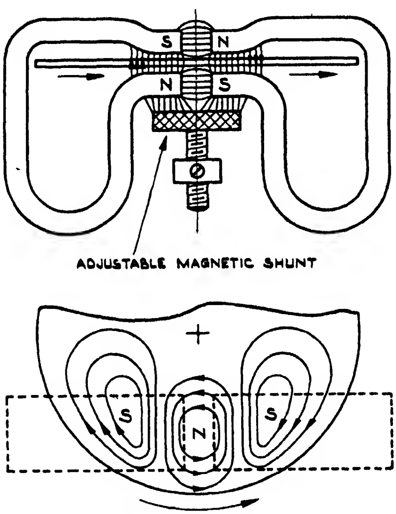


FIG. 16.—Dual brake-magnet system with adjustable magnetic shunt.

and proportions of the airgap in which the rotor moves. This is illustrated in Figs. 15 and 16, the first of which shows one form of magnet commonly employed in a single-magnet system, although it may also be employed in a dual-magnet system and the second of which shows a form of magnet confined solely to a dual-magnet system. The important distinction between the two forms lies in the airgaps and not in the magnets themselves. In Fig. 15 the brake flux is confined in a small, well-defined area, producing a relatively high flux density in the airgap, whereas in Fig. 16 the brake flux from each magnet is distributed over a larger and not so well defined area and the flux density in the gap is lower; the former is more efficient as a

brake-producing medium per unit weight of steel employed and if cobalt steel or nickel-aluminium steel is used, a single magnet having poles as shown can easily produce more braking torque than the dual-magnet arrangement. The single magnet must of necessity be adjustable in position in order to vary the brake, whereas the dual-magnet system can be fixed in position and the brake varied by means of a magnetic shunt. Where two magnets are used in this manner the one is magnetized in the opposite direction from the other. The magnetic shunt consists of an iron disc having a knurled edge and is mounted on a micrometer screw; by turning the disc so that it approaches nearer to the magnet poles, part of the flux is diverted from the magnet gaps and the rotor moves faster in consequence. According to B.S. 37: 1937, Clause 46, the manufacturer of a meter is required to provide for the use of the purchaser a range of adjustment of at least 7½ per cent. in either direction at full load. Thus, at least 15 per cent. range of adjustment must be available for the purchaser and since the manufacturer also requires something additional for his own use in making the initial calibration a total range of not less than 20 per cent. minimum is required.

To ensure that the initial accuracy of a meter shall not change with time, it is essential that the brake magnet shall be stable and not liable to increase or decrease in strength under service conditions. After a magnet has been magnetized, a settling down process or ageing effect takes place during which the magnet becomes progressively weaker. This loss of magnetism is relatively rapid at first, but after a lapse of years or even months may be very slow. The amount of the loss depends upon the coercive force of the steel used in the manufacture of the magnet and also on the relative proportions of the magnet and the airgap in which the disc rotates; the loss of magnetism is accelerated by vibration, repeated heating and cooling, and by the repeated application of small demagnetizing forces. Magnets of chrome or tungsten steel having a coercive force of 60 to 70 units show the greatest loss of magnetism, which may amount to 15 per cent. or more of their initial strength after being magnetized to saturation. The cobalt steels which have from 3 per cent. to 35 per cent. cobalt content and a coercive force between 110 and 250 units may lose 9 per cent. to 3 per cent. respectively of their initial strength. Finally the nickel-aluminium and the nickel-aluminium-cobalt alloys having a coercive force of 400 to 550 units will lose a very small proportion, probably not more than 1 to 1·5 per cent. of their initial strength.

As the natural ageing process in a magnet takes a very long time before stability is reached it is customary for manufacturers to magnetize all magnets to saturation and then subject them to a process which accelerates the natural inevitable loss. This process consists in subjecting the magnet to a demagnetizing force much greater than any which is likely to arise under working conditions and possibly, in addition, to strike the magnet several smart blows with a mallet, which has the same effect as vibration; this reduces the necessary storage time for ageing to six months or less and enables unstable magnets to be eliminated. In the case of chrome or tungsten steel magnets, which have the lowest coercive force of any type of brake magnet, a good estimate of the coercive force can be ascertained during the tests. After magnetization to saturation the brake force is measured on an instrument producing a constant driving torque. The magnet is then partially demagnetized by subjecting it to an alternating field produced by a single turn carrying a definite current, usually of the order of 150 to 200 amperes and maintaining this demagnetizing force for, say, ten seconds. Thus, on a 50-c/s supply, the magnet is subjected to 1,000 reversals of the demagnetizing force. Following this treatment the brake force is again measured under identical conditions and the difference between the two readings is a measure of the coercive force. The greater the coercive force the less will be the reduction in brake force and any magnet which does not come up to the required standard is rejected as likely to be unstable under working conditions. During the period of storage after demagnetization, the magnets are tested for variation in strength and if the artificial ageing has been satisfactorily carried out, no further falling off in strength will take place; any doubtful magnets can be kept under observation until it is demonstrated that they have reached stability.

Magnets of the cobalt and nickel-aluminium series lose very little strength when subjected to a demagnetizing force of 200 ampere turns, but it is not necessary to increase this force as it is much greater than any to which the magnet will be subjected under working conditions. Care must be exercised to ensure that any demagnetizing force is applied uniformly throughout the length of the magnet: failure to observe this precaution may result in local demagnetization and if for example the steel in the region of the magnet poles is demagnetized to a greater extent than in the body of the magnet there may be an apparent increase in the strength of the magnet in course of time. It is of course impossible for a magnet to increase in strength without the application

of a magnetizing force, but it is possible for the brake force to increase after local demagnetization around the poles due to an equalization of the forces in the body of the magnet. Such an effect would result in the meter becoming slower at all loads after a few years in service. The phenomenon of local demagnetization in a magnet is only possible where the coercive force in the steel is very high as is the case in magnets with a high cobalt content and the nickel-aluminium series. In the case of nickel-aluminium steels it is considered undesirable to apply considerable demagnetizing force as stability is likely to be impaired thereby.

3.4. Inductive Load Adjustment. Brief reference has been made on page 48 to the phase compensating loop, more commonly known as the quad band, which is usually fitted on the middle limb of the voltage electromagnet. The function of the quad band is to increase to 90 deg. the phase displacement of the voltage flux (leakage), behind the applied voltage, where the natural phase displacement is less than this amount. With this object in view, the quad band is made adjustable so that it can be moved and secured in position on or near to the lower extremity of the middle limb of the electromagnet. Moving the quad band from the extremity of the pole towards the voltage coil increases the phase displacement of the flux and causes the meter to run faster on inductive loads. As a matter of fact, it is necessary in practice to increase the phase displacement by ½ deg. or more, beyond the 90 deg. position in order to get the best results. If a meter is connected to an artificial oad with full-load current through the current coil and normal voltage on the voltage coil, and the phase displacement of the current is adjusted to lag exactly 90 deg. behind the voltage, the rotor should not move as the power-factor is zero. If this condition is achieved the meter should, theoretically, be correct at all power factors between zero and unity; in practice, however, it is found that the meter is slow at the imtermediate power factors. The reason for this discrepancy is that when the rotor is stationary at zero power factor the braking effect of the current flux is absent. If this braking effect were also absent at intermediate power factors the meter would be correct, but since it cannot be eliminated some compensation must be introduced. It will be appreciated that with any particular value of the current in the main circuit, the driving torque acting on the rotor will be twice as great at unity power factor as at 0·5 power factor, but the current braking force will be the same; the retarding effect of current braking will therefore be twice as great at 0·5 power factor as at unity power

factor for the same current value. By increasing slightly the phase displacement of the voltage flux, the driving torque at 0·5 power factor can be proportionately increased and the error eliminated. From 0·5 down to zero power factor a small but increasing positive error will be observed, but as loads having a power factor lower than 0·5 are uncommon and probably of short duration this error is usually of no practical importance.

Instead of employing a quad band which is moved in order to make the necessary adjustment, some makers prefer to wind a few turns of copper wire round the extremity of the voltage electromagnet pole and connect the ends of the coil so formed to a loop of resistance wire having an adjustable bridge sliding thereon. Movement of the bridge, by varying the amount of resistance in the circuit, permits the current in the coil to be varied. This method is usually adopted where access to the quad band for the purpose of adjustment is difficult. It has the advantage that a wider range of adjustment is possible on the wire loop than on a single quad band.

In some makes of meter the arrangement of the magnetic circuit is such that the natural phase displacement between the voltage and current fluxes at unity power factor is practically 90 deg., or it may be even a little more. This condition may arise in meters which employ a magnetic shunt across the current electromagnet poles or a tongue of magnetic material between these poles. According to Clause 46 of B.S. 37: 1937 the manufacturer of a meter is required to provide for the purpose of calibration such facilities for adjustment that the purchaser can change the speed of the rotor at 0·5 power factor by at least one per cent. in either direction. Since the manufacturer must also have some means of adjustment for the initial calibration in addition to that provided for the user, it follows that the full range of the adjusting device must be 3 per cent. or more. This determines the minimum size of quad band or equivalent device to be provided and in the case of meters where the phase displacement is already 90 deg. or thereabouts, creates a difficulty in that the smallest quad band which can be fitted is too large since the amount of compensation cannot be reduced to zero: the difficulty is surmounted by deliberately overcompensating the meter and then providing adjustable means for nullifying the excess. As already explained, the effect of a short-circuited winding or loop around the voltage electromagnet pole causes the flux passing through the loop to lag slightly; a similar lag in the current flux can be produced by surrounding the poles of the current electromagnet

with a closed loop. Any lagging effect on the current flux is equivalent to the cancellation of a corresponding lag in the voltage flux. In meters where a natural lag of 90 deg. or thereabouts in the voltage flux cannot be avoided, this lag is deliberately increased by fitting a quad band on the voltage electromagnet, which is not adjustable. The inductive load adjustment is then effected by winding a few turns of wire around the current electromagnet poles and connecting the ends of the winding so formed to a loop of resistance wire having a sliding bridge-piece, whereby the resistance may be varied as desired. This adjustment can be used to cancel such proportion of the excessive lag as may be necessary.

3.5. Low-Load Adjustment. A commercial-grade single-phase meter rated according to the provisions of B.S. 37:1937, will have a characteristic curve similar to that shown in Fig. 47 on page 111. In the absence of means for carrying out adjustments at low loads, the curve will exhibit a droop which becomes very noticeable from 20 per cent. load downwards. The main factors which contribute to this droop are: (1) low permeability of the iron in the current electromagnet and (2) friction in the rotor bearings and in the register driven by the rotor. In addition, careless assembly resulting in lack of symmetry between the voltage and current electromagnets may accentuate the droop, or on the other hand may tend to reduce it according to the position of one electromagnet relative to the other. As regards the permeability of the iron, this is referred to in the succeeding chapter on page 117 and all meters of a particular type are likely to be affected to the same extent. Friction on the other hand can be affected by the quality of the workmanship and will vary with the gear ratio of the register which is being driven. Thus, the work done by the rotor in driving the register will be greater in a 10-ampere meter than in a 2·5-ampere meter, since the indices will move four times as fast in the former at any selected load. A limit to the effect of register friction is imposed by Clause 35 of B.S. 37: 1937, which stipulates that the entire disconnection of the registering mechanism shall not affect the speed of the rotor at one-twentieth load by more than 1·5 per cent.

Friction in the top bearing of the rotor and between the bottom pivot and jewel can be an important factor, but when the meter is new and these components are well made the effect of this source of friction is usually much less than register friction; on the other hand, after the pivot or jewel has worn, friction in the bottom bearing may assume serious proportions.

In order that the lower part of the error curve may be improved, a low-load adjustment is provided. This consists of a plate or loop of non-magnetic metal, usually brass or copper, located in the gap between the current and voltage electromagnets or surrounding the middle limb of the latter. The induced current in this plate or loop is substantially in phase with the eddy currents induced in the rotor disc by the voltage flux. The reaction between the two resulting magnetic fields creates a small driving torque, the magnitude and direction of which will depend upon the position of the loop. By swinging the adjustment from one extremity to the other, the rotor can be made to move slightly in the forward or the backward direction on no load, or an intermediate position can be found where no movement takes place. It will be appreciated that the induced current in the low-load adjusting plate will have a lagging effect on the voltage flux exactly the same as in the inductive-load adjusting plate. The low-load adjustment is therefore complementary to the inductive-load adjustment insofar as its effect on the phase displacement of the voltage flux is concerned. Meters have been made in which one plate only has been provided for both purposes; a vertical movement serving for inductive-load adjustment and a horizontal movement for low-load. This arrangement is not very satisfactory however, since one of the movements invariably affects the setting of the other to a small extent, and further, as a very slight movement in the horizontal direction has a considerable effect on low loads, the adjustment becomes too coarse for convenience and accuracy.

An alternative arrangement to the plate or loop of non-magnetic metal which is occasionally used consists of a flag or vane of iron, placed in the leakage field adjacent to the middle voltage pole and provided with means for swinging from side to side. In this manner, a slight dissymmetry of the voltage flux can be created, the effect of which is the same as that created by an induced current in a plate which may be moved from side to side. The low-load adjustment is usually made with a voltage applied to the electromagnet, 10 per cent. in excess of the normal, and is set so that the rotor just fails to move in the forward direction when the meter case is lightly tapped. If the adjustment is correctly made the rotor should commence to move with a very small current passed through the current coils and the error at one-twentieth load will be very small.

A meter tester will know from experience the setting to make to achieve the best results on one-twentieth load. In calibrating a meter,

the "creep" or "shunt adjustment", as it is called, is made before setting the brake magnets for full-load adjustment. A check on one-twentieth load follows and if the creep adjustment was correctly made no further adjustment should be necessary. It may be found, however, that some slight alteration to the speed of the rotor on one-twentieth load is desirable in order to keep the error at this load within the desired limits. In such circumstances an alteration in the adjustment may result in a tendency for the rotor to creep forward or backward on no load and correction of this tendency will reinstate the low-load error which the previous adjustment had eliminated.

In order to permit adjustments to be made on low loads without introducing "shunt running" or "creeping" of the rotor on no load, a variety of anti-creep devices are provided in different makes of meter. The most commonly used anti-creep device consists of two small holes pierced through the rotor disc at diametrically opposite points in such a position that they pass into the leakage field from the shunt electromagnet when the rotor revolves. The effect of a hole entering this field is to cause a diversion in the path of the eddy currents and to set up a local attraction between the hole and the pole of the electromagnet. The attractive force is very small and varies according to the diameter of the hole and the distance it is spaced from the centre of the disc. These proportions are determined by the manufacturer and the force of attraction is sufficient to permit the meter being set two or three per cent. fast on one-twentieth load without incurring the risk of creeping on no load. It is not necessary to have two holes in the disc as one will serve equally well, but may result in an unbalanced rotor which will be unreliable on starting-current test.

Instead of introducing holes, some manufacturers prefer to make a small slit in the periphery of the rotor disc, extending $\frac{1}{32}$ in. to $\frac{1}{16}$ in. inwards: the effect of this is similar to the effect produced by a hole in that it causes a diversion in the path of the eddy currents when the slit is in the leakage field of the voltage electromagnet. Another alternative, commonly adopted by Continental manufacturers, consists in securing a short iron wire or tongue on or adjacent to the rotor shaft in such a position that, in revolving, the wire comes within the influence of the magnetic field from the brake magnet or the voltage electromagnet; the attraction between the two can be varied by bending the wire nearer to or away from the magnet in question.

After all adjustments have been made the rotor must start and continue to run indefinitely with a current equal to 0·5 per cent. of the

rated current when the marked voltage is applied to the voltage circuit, or the minimum voltage where a range of voltage is marked, under a condition corresponding to unity power factor in the main circuit. It usually happens in practice that after the low-load adjustment has been correctly made, the adjusting device will be found to be nearer to one extremity of its range of movement and not in a central position. This is inevitable owing to slight but unavoidable irregularities in manufacture, and in order that the purchaser of a meter may have facilities for further adjustment, Clause 46 of B.S. 37: 1937 stipulates that, as delivered to the purchaser, the low-load adjusting device shall be capable of further movement in either direction to provide for two per cent. change in speed at one-twentieth load.

The small auxiliary torque developed in the rotor by the low-load adjusting device varies as the square of the voltage applied to the voltage electromagnet. It follows therefore, that if the voltage is raised or lowered, the low-load error will have corresponding variations. The effect of an increase in voltage on the error of the meter is to make the meter faster on low loads, and a reduction in voltage will make the meter slower; this is the opposite from the effect produced on high loads and consequently two error curves taken, one at a high voltage and the other at a low voltage, will cross at some point usually in the region of 20 per cent. to 25 per cent. of rated full load.

3.6. Registering Mechanism. Three different types of registering mechanism have been used in the past, in conjunction with electricity meters, namely, jumping-figure cyclometer, creeping-figure cyclometer, and pointer types. The pointer-type register is the only one which complies satisfactorily with the requirements of British practice, although the cyclometer types are used extensively on the Continent where requirements are less stringent. Superficially it may appear that cyclometer registers have advantages which are not possessed by other types and as advocates of the former come forward from time to time, it may be worth while to consider briefly the advantages of the various types and the conditions which have to be met. The requirements of the registering mechanism are detailed in B.S. 37: 1937, Clause 35, and include in effect the following:

1. The registering mechanism of the meter shall be of the pointer type.
2. There shall be not less than six pointers and circular scales.
3. The fastest moving index in a meter having a full load of 2·5 kW shall make 25 revolutions per hour at full load.

4. The entire disconnection of the registering mechanism shall not affect the speed of the rotor at one-twentieth load by more than 1·5 per cent.

The third requirement detailed above is derived from a table giving particulars of the circular scales for all ratings of meter and represents the most difficult case from the point of view of the frictional load imposed on the meter.

3.7. Jumping-Figure Cyclometer Register. The cyclometer register with jumping figures, sometimes called a "jump counter", consists of a dial having five openings, behind each of which a disc is located. Each disc is numbered 0 to 9 and apart from the fifth and fastest moving disc, only one figure is visible in an opening at any time. The fifth disc moves slowly when the meter is registering consumption and at times two figures may be visible through the dial opening. When the figure 9 appears in the fifth opening, this figure remains stationary while the registration continues until the next figure which is 0, is due to appear; at this instant the figure 9 disappears and 0 jumps into position, the adjacent figured disc advancing one division simultaneously. The drive between any one figured disc and its neighbour higher up the scale is through a Geneva movement which effects a rapid changeover. Thus the change from 0000·9 to 0001·0 or from 0999·9 to 1000·0 would take place instantaneously and since it is beyond the capacity of the rotor to provide the power to carry out this operation at the instant when the changeover occurs, it is necessary to store energy which can be released periodically as required. The heaviest load occurs when the reading 9999·9 has been reached and the register changes over to 0000·0 as on this occasion all the figured discs have to spring over simultaneously. Although this operation only occurs at infrequent intervals, it is necessary to store sufficient energy for its accomplishment and this energy must be accumulated whether the register is turning over two discs only or all five discs. The sixth and fastest-moving index in this type of register is a pointer moving around a scale and this is provided in order that accurate observation of short-time tests can be made.

The storage of power for actuating the changeover of the discs is accomplished by winding up a spring or by raising a weighted arm; at the appropriate moment this power is released by releasing the spring or by causing the weighted arm to tip over and fall by gravity, imparting motion to one or more discs in so doing. It will be appreciated

that this stored power is derived from the rotor and is the equivalent to a frictional load. The effects of a frictional load on the accuracy of the meter are referred to elsewhere and these effects are particularly undesirable if the friction is of a variable character as compensation cannot be effectively applied. In this case the load is variable since in winding up a spring or a weighted lever the reaction is small at first but increases to a maximum after which, on the release of the stored power, the cycle of operations recommences. A partial mitigation of these ill effects may be secured by introducing a counterweight, but this merely reduces the difference between the maximum and minimum loads imposed on the rotor without in any way reducing the total amount of work to be done.

The work which the rotor is called upon to perform, in overcoming friction in the register, varies with the rating of the meter. The heaviest load occurs in meters of 2·5, 25 and 250 kW ratings, since in these the number of revolutions of the rotor per revolution of the fastest-moving figure disc is the lowest. Take for example a 2·5 kW meter which may be rated at 10 amperes 250 volts and which has a rotor speed of 25 revolutions per minute at full load; this corresponds to 1,500 revolutions of the rotor per hour, during which time 2·5 kWh will be registered. A 25 kW or 250 kW meter will have exactly the same gear train but the dial will show respectively 10 or 100 times the values shown on the 2·5 kW register. The fastest-moving figure disc in the 2·5 kW register makes one revolution per kWh or one revolution for 600 revolutions of the rotor. Sufficient power must be stored during 600 revolutions of the rotor, to turn one or all of the succeeding figure discs at the appropriate time and as the frictional load reaches a maximum immediately prior to the changeover, the meter may stop if at this time it is operating on a small load.

Because the frictional load due to this type of register is so variable it is necessary to store sufficient power to overcome the maximum friction which is likely to arise. If insufficient storage is provided, the figures instead of jumping into position are likely to change over slowly; this results in difficulty in ascertaining the correct reading, as two figures may be partly visible in one or more of the dial openings at the same time. The main object of the jumping-figure cyclometer-type of register is to provide at all times a clear and easily-read indication of the state of the meter, free from ambiguity. This can only be achieved at some sacrifice in the accuracy of the meter, particularly at low loads and an inevitable variation in the error: on the other hand

it does permit an unskilled meter reader to make an accurate reading in a minimum of time.

3.8. Creeping-Figure Cyclometer Register. The cyclometer register with creeping figures, sometimes called a "roller counter", consists of a dial with six openings behind each of which a roller is located. Each roller is numbered 0 to 9 around the periphery and the fastest-moving roller is sometimes provided with 100 small divisions, with the object of enabling more accurate readings to be taken. The sixth roller moves slowly when the meter is registering consumption and as one figure is disappearing and the next appearing, both can be seen in the dial-opening at the same time. As the figure 9 is passing and the figure 0 is appearing in the opening, a projection on the side of the roller engages with a pinion; this pinion is also in engagement with the adjacent roller of higher denomination and the two rollers move together until the last-mentioned has advanced one division. The first roller then disengages from the pinion and continues to advance independently. In due course the second roller will have advanced until the reading on the register is 000099 and is about to change to 000100; at this point a second pinion will engage the second and third rollers and the three rollers will move together until the third roller has advanced one division, after which the first roller will again continue its independent movement.

In a 2·5 kW meter, the first and fastest-moving roller corresponding to the index-finger in the jumping-figure cyclometer will make one revolution for one-tenth of a kWh. Continuing with the example cited in the earlier paragraph dealing with the jumping-figure cyclometer register, the rotor will make 60 revolutions for one revolution of the first roller. During an interval represented by one-tenth of a revolution of the roller or six revolutions of the rotor the frictional load is increased as two rollers are turning simultaneously. At intervals represented by 600 revolutions of the rotor the frictional load is further increased by the necessity for turning three rollers, and at proportionately longer intervals, four, five or six rollers and their driving pinions must be turned simultaneously. This progressively-increasing load produces a cyclic variation in the frictional load on the rotor with corresponding variations in the meter error, the effect of course being to make the meter register less than the correct amount or in extreme cases to cease registration altogether. The cyclic variations in friction when two or three rollers only are driven are perhaps less serious than is the case with the jumping-figure cyclometer register, but when four,

five or six rollers are driven, the frictional retardation may be greater. Owing to the fact that the rollers change position slowly, it is sometimes difficult to make a correct observation of the reading, particularly when several of the rollers are in process of changing from 9 to 0. At other times however, when the figures are clearly visible in the dial openings, an unskilled observer can read the meter with ease.

3.9. Pointer Register. The pointer type of register having six pointers and circular scales is without question the most satisfactory register from the point of view of friction. The wheels and pinions are usually machine-cut and introduce less friction than the cyclometer registers; furthermore the friction is substantially constant and can be compensated for by means of the low-load adjusting device. Advocates of the cyclometer register usually claim that the cyclometer is easier to read and under favourable conditions, when there can be no ambiguity as to the figures in the openings, this claim must be admitted so far as unskilled observers are concerned. The trained meter-reader, however, can read a pointer register just as easily and quickly as a cyclometer and it is a fact that in areas where both types of register have been in use, the percentage of incorrect observations made by skilled meter-readers is approximately the same for both types. The reason for this is that after the reading has been correctly taken a mistake has been made in recording the reading on the meter-card or book, a mistake which is liable to occur irrespective of the type of register.

The effect of register friction on the accuracy of the meter can be determined by making tests on one-twentieth load, with and without the register in engagement with the rotor. The difference between the errors is a measure of the frictional retardation introduced. As the error at this load may not be constant, it is desirable to make at least six observations under each condition and take the difference between the average errors so determined: the difference between the errors under both conditions should not exceed 1·5 per cent. It is usual to remove the register from the meter in carrying out this test, but certain makes of meters have registers constructed with magnetic material which is in proximity to the brake magnet. In such cases, the entire removal of the register affects the brake force of the magnet and introduces a difference which cannot be separated from the effects of friction; it is desirable therefore to make certain that the register is non-magnetic before carrying out this test, or alternatively to disengage the first wheel which meshes with the pinion or worm on the rotor-shaft.

In carrying out the test for register-friction the meter should be free from vibration, which will tend to reduce friction by loosening up the gears, and if a cyclometer register is under test, observations should be made during the time when the springs or weights are being wound up, or the rollers are turning over between the 9 and 0 positions. In comparing one make of meter with another, a true comparison can only be made if meters of the same rating are being compared. The gear ratio between the rotor and the first index in the register varies with the rating and naturally this will have some influence on the results obtained. Thus, for example, meters running at 25 r.p.m. on rated full load and having ratings of 2·5, 5 and 10 amperes at 250 volts will have gear ratios of 240/1, 120/1 and 60/1 respectively, between the rotor and the first index in the register. It is obvious that the lower the gear ratio the greater will be the work done by the rotor in driving the register. This will be particularly noticeable in the case of cyclometer registers, the discs or rollers of which have to be turned over four times as often in a 10-ampere meter as in a 2·5-ampere meter.

Efforts to compare the friction of one make of register with another are sometimes made by removing the register and spinning the first wheel which engages with the rotor. If the first wheel in one register spins longer than the corresponding wheel in another, it is sometimes assumed that the one spinning the longer has the least friction. Such a method of comparison is crude and is quite valueless and misleading; the duration of spin will depend upon the gear ratio of the register and the diameter and weight of the first wheel as well as upon the friction. Obviously, the heavier the first wheel and the larger its diameter, the more energy can be stored in it at a given speed of rotation; this method completely ignores the friction at the point of engagement between the rotor and the register which may in fact be considerable if correct depth of engagement is not achieved. The only useful purpose served by trials of this nature is in comparing registers of identical construction and gear ratio. In such a case it may be possible to discover quickly, a register with an excessive amount of friction, but for a reliable comparison a test on a meter working on a low load is desirable.

3.10. Rotor. The rotor is that portion which forms the prime movement of a motor-type meter; in the case of a single-phase meter, the rotor invariably consists of an aluminium disc mounted on a vertical spindle which is supported between top and bottom bearings. The complete rotor usually weighs between 12 and 26 grams. A high ratio

of torque to weight is desirable, other things being equal, and as the spindle contributes nothing to the torque, it is of the lightest construction consistent with strength.

The disc is blanked out of aluminium strip or sheet which must be pure to ensure the highest conductivity, free from any trace of magnetic inclusions which will detrimentally affect the starting-current, and uniform in thickness throughout. The rolling process to which the strip is subjected during manufacture leaves the metal with a comparatively hard skin on each side, which is in a state of tension. After blanking there may be a tendency for the metal to warp in course of time, due to the tension on one side exceeding that on the other. This tendency is more pronounced in the thinner discs and to counteract it the discs are frequently stippled or corrugated. The stippling is produced by placing the disc between two steel dies in a press; the faces of the dies are covered with diamond-shaped projections which are forced into the surface of the disc under heavy pressure. After one blow has been struck the disc is turned in a horizontal plane through an angle of about 60 deg. and another blow is struck.

The effect of this stippling process is to flatten the disc and to cover the surface with a large number of small indentations. This breaks up the stresses which existed originally and introduces a large number of local stresses which mutually cancel out, leaving a surface free from any tendency to distortion in any particular direction. It is important that the stippling dies be made of non-magnetic steel, as the extreme points of the diamond-shaped projections occasionally break off and become embedded in the disc. The reduction in the diameter of the discs in modern meters has reduced the risk of buckling through ageing, and the stippling is becoming of less importance than it was when the discs were frequently four inches or more in diameter.

The rotor of an alternating-current meter, in addition to being a source of rotary motion is the seat of a number of parasitic forces which may have undesirable effects. When the voltage electromagnet only is energized and no current is passing through the current coil, the disc is subjected to the influence of an alternating flux. Assuming that the supply frequency is 50 cycles per second, this flux starting from zero, rises to a maximum and dies away to zero a hundred times per second. Each time a pulse of flux cuts through the disc the latter is repelled from the electromagnet pole and tends to vibrate in unison with the pulsations in flux.

The current electromagnet when energized also exerts similar repulsive forces on the disc, but from below instead of above; the magnitude of these forces varies as the square of the flux producing them. When the meter is carrying a load, the power factor of which is unity, the repulsions exerted by the current flux will occur at instants of time intermediate between the repulsions exerted by the voltage flux. As the alternations of force are exerted from opposite sides of the disc, they tend to increase the amplitude of any movement which may occur. If the power factor of the load were zero the repulsions exerted by the two fluxes would occur at the same instant and would tend to cancel out.

The effect on the disc of this tendency to vibrate, depends upon its natural period of vibration and may be manifested in the form of a humming noise: it may occur when there is no load on the meter, that is, when the voltage electromagnet only is excited, or alternatively at some particular load or power factor. It is one of the most elusive of troubles as all experienced designers will agree and many a meter which would emit a loud noise on consumers' premises, will steadfastly refuse to make a sound when returned to the manufacturer. Not infrequently a distorted wave form in the supply voltage has been responsible for the creation of noise and in test rooms, the use of a particular generator or transformer has been associated with this phenomenon.

Vibration of the disc may or may not result in noise but it frequently results in a minute movement of the bottom pivot over the surface of the jewel. In addition to the forces acting vertically on the portion of the disc between the electromagnet poles, there are other parasitic forces acting laterally. These are due to the induced currents in the disc, circulating in the region of the brake magnet poles. The induced currents are of course alternating, whereas the permanent magnet field is unidirectional, with the result that a minute force is set up in that portion of the disc between the brake magnet poles tending to cause a lateral movement of the disc; the magnitude and direction of the force will depend upon the position of the brake magnet with reference to the voltage electromagnet and the distance between the two. Obviously the further they are apart, the weaker will be the induced current in the portion of the disc under the influence of the permanent magnet field and the smaller the movement produced.

From the foregoing observations it will be appreciated that the effect of the various parasitic forces acting in the rotor is somewhat

complex. These forces are difficult to analyse and their effects cannot always be foreseen: they differ in every type of meter and frequently are more pronounced at one critical frequency. Before a standard frequency was adopted in Britain, supply frequencies varied between 25 and 100 cycles per second, and all manufacturers will be aware of difficulties in avoiding noise at some particular frequency. The type of noise may vary from a low hum to a high-pitched musical note, or a rattle. In some cases a periodic repetition of the noise occurs, synchronizing with the rotation of the disc, and in other cases a rattle in the top bearing or a dancing of the bottom pivot on the jewel is observed. The diameter and thickness of the disc and the length and springiness of the rotor shaft are among the factors which influence the production of noise. It is practically impossible to avoid vibration in some degree in a rotor, but any resulting noise usually emanates from the bearings which are the supports for the vibrating body.

The revolutions of the rotor are communicated to the register through a pinion or worm on the rotor-shaft engaging with a cross-wheel or worm-wheel respectively on the register. It is usual for the disc to be located at the bottom of the rotor-shaft in order to keep the centre of gravity of the moving system as low as possible. This reduces side-thrust between the top pivot and top bearing, and in fact, if the centre of gravity is kept below the end of the bottom pivot, there is no side-thrust and the rotor can revolve with the top bearing removed. The pinion or worm on the rotor-shaft will be located as near the top as practicable. A pinion-drive results in some side-thrust on the top pivot, and a worm-drive produces end-thrust and side-thrust. With a right-hand thread on the worm and a rotor moving from left to right as is usual, the end-thrust will tend to take weight off the bottom bearing of the rotor.

A pinion-drive is sometimes advocated by the manufacturers using this as being superior to a worm-drive, because its efficiency is claimed to be higher. This may be true if the gear reduction is the same, but in practice this is seldom the case. With a pinion-drive the highest practicable reduction is about 16 to 1 in one stage, whereas with a worm-drive a reduction of 40 to 1 is easily achieved and 80 to 1 is practicable. In any case, with a vertical rotor-shaft and horizontal pointer-arbors in the register, a worm-drive is essential at some stage in the transmission between rotor and first pointer, unless a bevel-drive which is more inefficient still, is incorporated. Allowing for a gear reduction of two or three times as much in the first stage by the use of a worm drive, it is

doubtful whether any gain in efficiency can be shown by the pinion-drive; on the other hand a wheel of coarser pitch can be used in a worm-drive, which permits more latitude in the meshing of the register. This is an advantage since shallow depthing of the wheel and pinion may result in locking the gears, whereas an error of the same magnitude between worm and worm-wheel would have little effect. On the whole there is no technical advantage to be gained by the use of a pinion-drive and considerations other than efficiency will determine which is the better to use in any given circumstance.

3.11. Rotor Bearings. The rotor bearings in a single-phase meter are, generally speaking, the only parts which wear out. They are also the main source of variable friction which develops in course of time and results in a permanent change in the error of the meter at low loads. When a meter is new and the parts have been well made, the initial friction in the rotor bearings is very small. In the calibration of the meter, compensation for the initial friction is made by means of the low-load adjustment and any error on this account can be eliminated. Provided that the strength of the brake magnet does not change, the only other factor likely to render the meter inaccurate is a change in the friction. This may be the result of foreign matter in the meter falling on the disc and entering the magnet gaps where it causes obstruction. Alternatively, friction may develop in the bearings due to wear and tear, or to the use of unsuitable oil which congeals or dries up.

The presence of foreign matter and the use of unsuitable oil are avoidable causes but worn bearings ultimately are inevitable. In a well-designed meter, however, and with carefully selected material, a reasonably long life may be expected before renewal of worn parts becomes necessary. Provision is usually made for facilitating the exchange of these parts and in some meters new bearings can be substituted without affecting the calibration. In some countries, periodical testing and inspection of meters is carried out *in situ* and the exchange of bottom bearings is part of the routine procedure. This practice does not find favour in Britain where it is preferred to exchange meters periodically and to carry out all tests and renewals in a properly-equipped test-room and repair department.

3.12. Top Bearings. The top bearing of a meter consists of a steel pivot working in a sleeve, usually of metal; wear of these parts due to rotation of the rotor is very small as there is very little side thrust. Vibration set up in the rotor due to parasitic forces may be communicated to the top pivot and under certain conditions can

result in noise or rattle and possibly wear. Noise is likely to be developed in some meters if too much play exists between pivot and sleeve; a normal allowance between the diameter of the pivot and the pivot hole is 0·001 in. to 0·0015 in. Even with this small clearance the pivot can shake about from side to side and cause considerable rattle, but a spot of suitable oil on the pivot will immediately silence the noise unless the pivot hole is too large. Meters have been made in which the rotor-shaft consists of a steel wire having suitably-shaped pivots formed on both ends or with provision for the attachment of suitable pivots. If such a shaft becomes magnetized, as it may do during manufacture or due to the proximity of a powerful brake magnet, alternate attraction and repulsion may result, owing to the influence of stray alternating flux from the voltage electromagnet. This vibration will be superimposed on the vibration caused by other parasitic forces and top-bearing rattle has been known to arise from this cause.

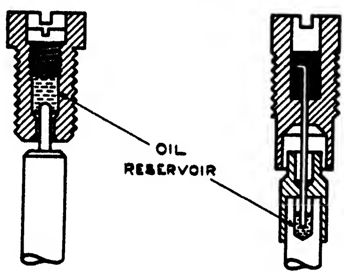
Most manufacturers make a practice of oiling the top pivot, partly with a view to the prevention of rust formation on the highly-polished surface of the pivot and partly to eliminate the development of noise. Oil is not used to reduce friction. Its presence in the pivot holes acts as a cushion and prevents metallic contact between pivot and sleeve. Many efforts have been made to provide an oil reservoir in the top bearing which will ensure an ample supply of oil in the pivot hole at all times. An excess of oil is undesirable in that it introduces a drag which will increase if the oil congeals in course of time. The ideal top bearing which will be silent under all conditions and which will maintain a plentiful supply of oil without permitting it to leak away or spread has probably not yet been invented.

Two forms of top bearing which have been used extensively are shown in Fig. 17. The first form (a) is very effective provided that there is a supply of oil in the reservoir. During transport, however, there is a tendency to eject some of the oil if up and down movement of the pivot takes place, resulting in flooding of the area around the pivot-hole. In the second form (b) the oil in the reservoir cannot rise up the pivot to the pivot-hole which tends therefore to run dry. After transport the pivot hole will retain for a time oil which has reached it due to the meter being inverted or laid on its back, but this will gradually gravitate into the reservoir.

The top pivot in this form is a polished steel wire, held in the top bearing screw and of sufficient length to ensure a certain amount of flexibility. The bearing is carried on the top of the rotor shaft and the

flexibility of the pivot, together with the presence of oil, helps to prevent rattle; a skirt on the lower end of the screw surrounds the top of the rotor-shaft and prevents damage to the flexible pivot due to excessive lateral movement. The oil reservoir in this form should not be completely filled, otherwise, during transport longitudinal movement will eject some of the oil which may get into the annular space inside the skirt of the top bearing screw; a drop of oil in this position will cause excessive drag on the movement of the rotor, resulting in low-load errors and poor starting performance.

3.13. Bottom Bearings. The bottom bearing of an alternating-current meter may be regarded as its most important organ. It shares, with the brake magnet, the responsibility for the sustained accuracy of the



(a) (b)

FIG. 17.—Top bearings with oil reservoir for alternating-current meters.

meter after its initial calibration. From the commencement of its working life it is subjected to forces tending to cause deterioration and a large amount of research has been carried out in this country since 1920 with the object of improving its efficiency and extending its working life. One of the earliest workers in this field was the late W. S. Sprague, followed by Stott and Shotter. The last has probably contributed more to the published information on the subject than any other individual.

The bottom bearing frequently consists of a steel pivot resting in a sapphire cup. The pivot may be a short length of hardened steel wire, hemispherical in shape at its lower extremity and highly polished; it is fitted into the lower end of the rotor-shaft in such a manner that it may be removed easily for inspection or renewal when worn. Alternatively it may take the form of a steel ball pressed into a hole in a short

brass stem slightly larger in diameter than the ball, the edges being spun over to retain the ball in position. The material used for the pivot is usually a high-carbon steel or a chrome steel and must be capable of withstanding very high forces in compression. The end of the pivot which is in contact with the jewel should be truly hemispherical, free from scratches or grinding marks and must have the highest polish obtainable.

The bottom jewel consists of a sapphire, the upper face of which contains a cup-shaped depression in which the bottom pivot of the rotor rests or rotates; like the pivot, the surface of the cup is highly polished. Sapphire is used because of its great hardness, being next in the hardness scale to diamond. The sapphire cup is set in a brass mount and fitted into the bottom bearing screw of the meter. Most manufacturers provide a spring support for the jewel in order to reduce the possibility of damage to the working face through impact if the meter is subjected to rough handling. The spring support, if suitably proportioned, also contributes to the elimination of noise and rattle. It is common practice, although not universal, to make provision for the removal of the jewel from the screw to facilitate examination.

The area of contact between the pivot and jewel is extremely small; the working faces have different radii, and theoretically contact between the two is established at an imaginary point having no area. The weight of the rotor, light though it is, resting on an imaginary point, would exert a pressure on its support amounting to an infinite number of tons to the square inch. In practice of course, no material can withstand such a pressure and the end of the pivot is deformed until the area becomes sufficient to resist further deformation. Even so, the average pressure is very high, being of the order of 30 to 80 tons to the square inch.

An examination of modern single-phase meters shows that the rotors weigh from 12 to 25 grams, pivots have radii of 0·014 to 0·030 in. and jewel cups have radii of 0·030 to 0·066 in. The ratio of jewel radius to pivot radius in individual meters varies between 1·4 to 1 and 4 to 1 in most cases. It will be appreciated that in the centre of the area of contact between pivot and jewel the greatest amount of deformation has occurred, whereas around the fringe of the area there has been no deformation. It follows that the intensity of pressure will be greatest at the centre and the maximum pressure at this point is substantially 50 per cent. greater than the average over the whole area.

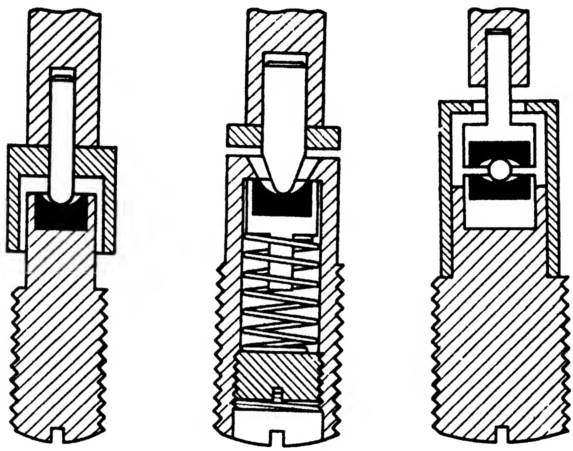
It is not surprising that under working conditions, with materials

stressed far beyond the limits usual in engineering practice, ultimate disintegration of the bearing surfaces should take place. With the continued movement of the pivot over the surface of the jewel, microscopic fragments of sapphire become detached and when these fragments get under the pivot, they become embedded therein and the pivot then proceeds to cut the surface of the cup; the end of the pivot also suffers from the cutting action of the sapphire and an amount of debris collects, which has the effect of slowing down the meter on low loads. Once this failure of the working surfaces has occurred further deterioration is rapid. The exchange of a worn jewel should always be accompanied by the exchange of the pivot as the one cannot wear without influence on the other, although the wear may not be very obvious.

In another form of bottom bearing, the conventional positions of pivot and jewel have been reversed; the steel pivot forms part of the bottom bearing screw and points upwards, while the inverted jewel cup is attached to the lower end of the rotor-shaft. The object of this arrangement is to allow the debris to escape from the inverted cup, but as it is no longer used it may be presumed that the disadvantages associated with the arrangement outweigh the advantages. A form of ball bearing is used by one manufacturer consisting of two sapphire cups, face to face, with a small steel ball placed between them. The advantage claimed for this arrangement is that the ball rotates between the cups and continually presents a new working surface. A number of types of bottom bearing are shown in Fig. 18.

It is now generally agreed that lubrication of the bottom bearing is desirable. Many kinds of oil have been tried and as a result of a long series of tests, Shotter recommends an oil known as Silvertown Meter Oil No. 2. This oil possesses the ability to withstand high pressure without rupture of the oil film and does not tend to become gummy in course of time; it remains fluid at the lowest working temperatures experienced in this country and it has the ability to retain debris in suspension for very long periods. This latter factor is important in that particles of sapphire or steel which become detached are carried away from the point where they can do further damage and they do not tend to gravitate back to the centre of the jewel cup. By the use of a suitable oil such as this, the number of revolutions made by the rotor before the bearing is worn out is multiplied many times. Other things being equal, a meter with a lubricated bottom bearing can remain in service much longer than one which is run without proper lubrication.

Reference has already been made to the effect of parasitic forces on the rotor. Even when there is no load on the circuit in which the meter is connected, the rotor is subjected to minute vibrations which cause the bottom pivot to move about on the surface of the jewel cup. These movements result in wear and destruction of the polished surfaces in course of time; in addition, rotational movement alters the path traversed by the pivot and as the load increases the pivot tends to run to one side of the jewel cup. Prolonged operation at a high load



(a) (b) (c)

FIG. 18.—Bottom bearings for alternating-current meters.

may result in cutting action taking place in the side of the jewel cup, well away from the centre.

3.14. Sapphire Meter-Cups. In a report dealing with research at the National Physical Laboratory on sapphire meter-cups, it was suggested by Stott that sapphire jewels, both natural and synthetic, cut in different directions relative to the crystal structure, would offer varying resistance to the effects of wear. Stott found that a jewel cut with its axis making an angle of approximately 90 deg. with the optic axis offered maximum resistance to wear. This fact has since been confirmed by Shotter and others in tests on unlubricated pivots and jewels. Good results have been obtained with jewels cut so that the axis of the jewel cup makes an angle of between 80 and 90 deg. to the optic axis.

In the opinion of the author, however, correct lubrication is more important than the orientation of the jewel cup and recent research tends to confirm this view.

Until comparatively recent times the number of sizes of sapphire meter-cups in use was very large, each meter manufacturer having his own standard dimensions and in some cases, cups of different dimensions in different types of meter. During World War II this diversity in dimensions created difficulties in obtaining supplies, and as a result of discussions between the meter manufacturers and the manufacturers of meter jewel-cups, agreement was reached to reduce the number of sizes called for. Following the conclusion of hostilities, it was agreed that some measure of standardization was desirable and most meter manufacturers accept as tentative standards, meter cup jewels to the

TABLE 1

Dimensions of Meter Cup Jewels

No.	Rondel	A		B		C		D		E
		Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Nominal
		in.	in.	in.	in.	in.	in.	in.	in.	in.
1	X	0·102	0·100	0·056	0·054	0·033	0·031	0·022	0·018	0·005
2	X	,,	,,	,,	,,	0·049	0·047	0·018	0·014	,,
3	X	,,	,,	,,	,,	0·064	0·062	0·013	0·010	,,
4	Y	0·090	0·088	,,	,,	0·033	0·031	0·022	0·018	,,
5	Y	,,	,,	,,	,,	0·040	0·038	0·018	0·014	,,

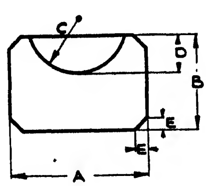


FIG. 19.—
Dimensions of jewel cup.

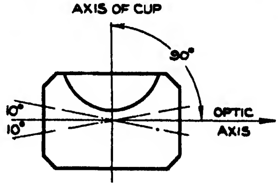


FIG. 20.—
Orientation of jewel cup.

dimensions detailed in Table 1 and of the form shown in Fig. 19. The principal manufacturers of jewel cups are prepared to supply oriented jewels to the limits shown in Fig. 20. The relationship between the axis of the jewel cup and the optic axis will be understood by reference to this figure.

It is not always practicable to adhere to these tentative standards, particularly where spare parts are required for meters supplied during the pre-war years, but it is generally agreed that in future designs and for current production, so far as is possible, the dimensions of the jewel shall conform to one of the five sizes detailed in Table 1. It will be noted that the short sapphire cylinders or "rondels" as they are called, are all of the same axial length and there is a choice of two diameters. The cups are of three different radii and five alternative combinations of these dimensions are available. It is believed that from this selection each manufacturer can obtain a jewel to suit his particular requirements.

At the present time practically all single-phase meters are fitted with synthetic sapphire cups. Sapphire, whether natural or synthetic, consists of aluminium oxide (Al_2O_3). The synthetic product is superior to the natural mineral in that it is usually free from inclusions of an objectionable character and lends itself more readily to economical manufacturing processes. Natural sapphire is often coloured, varying from blue to pale blue, pink, rose or red. The colour is due to the presence of metallic salts and it is this which gives sapphire its value as a gem stone. Ruby is actually sapphire having a rich red colour. For meter jewel-cups, however, a colourless stone is preferable, as defects are more readily observed.

In polyphase meters or meters having comparatively heavy rotors, diamond is sometimes used in preference to sapphire. It is the hardest known material and because of this, its life as a meter bearing is considerably longer than sapphire; its cost is very much higher but this may be justified in some cases where large sums of money are dependent upon the sustained accuracy of a meter on low loads. Because of its extreme hardness, it can only be ground to shape and polished by means of diamond dust and it is not economical to produce cups to the dimensions shown in Fig. 19. In view of the excellent performance which can now be obtained with oriented sapphire bottom bearings and proper lubrication, it is probable that the cost of diamond bearings will no longer be justified in many cases where they have been used previously.

3.15. Single-Phase Three-Wire Meters. Although single-phase three-wire meters are little used in Britain, they are used extensively on the Continent and in America and Canada. Their constructional features are identical with the single-phase two-wire meter with the exception of the current electromagnet, which has two current windings connected

one in each of the outer conductors of the three-wire system; the voltage coil is connected between the two outer conductors. If the current electromagnet core is of ⊔-shape, each current winding may be confined to one limb; in some cases however, the two windings are distributed similarly on both limbs, each winding occupying the top half of one limb and the bottom half of the other. This latter arrangement is preferable from the point of view of accuracy when the currents are unbalanced, but is more difficult to assemble and to insulate satisfactorily in the larger current ratings.

In using this form of meter, the assumption is made that the voltages on the two halves of the three-wire system are equal. If this assumption is not justified, the meter will be inaccurate on unbalanced loads. Consider the case of a 10-ampere, 2 × 110-volt meter in which, for example, a current of 10 amperes is flowing in one half of the system and no current in the other half, the voltage across the outers being 220 volts and the power-factor unity. The registration on the meter will be proportional to 10 amperes at 110 volts irrespective of the actual voltage across the half of the system to which the load is connected. If the voltage is 5 per cent. low on one half and 5 per cent. high on the other half, the meter will be in error to the extent of 5 per cent. Apart from this error, the meter has the disadvantage that if the main fuse is blown on one of the outers, the voltage electromagnet will not be energized; the consumer can still obtain a supply on one half of the system however, but there will be no registration on the meter. The remedy for both these disadvantages is to use two single-phase two-wire meters, connected one in each outer conductor, or alternatively and preferably, one two-element meter identical with a three-phase three-wire meter as used on polyphase circuits.

3.16. Connection Diagrams. The connections for a single-phase two-wire meter are arranged as in Fig. 21 (a). Where one pole of the supply is earthed, as is usual, the current coil is connected in the un-earthed conductor. If the meter is wrongly connected in the earthed conductor, the consumer can, by establishing another earth connection on his own side of the meter, short-circuit or shunt the meter current coil and thus substantially reduce the registration. Such an artifice is very difficult to discover and does not interfere in any way with the working of the consumer's installation. A disconnecting link is provided in the terminal block, between the terminal connected to the current coil and the terminal connected to the voltage coil, in order to separate the two circuits for testing purposes. Correct installation is therefore imperative.

Where heavy currents are metered and the use of a current transformer becomes necessary, the connections are arranged as in Fig 21 (b). In this case the terminals of the voltage coil are entirely separate from the current terminals and no disconnecting link is necessary. The current winding of the meter is wound for five amperes. In circuits above 600 volts, it is customary to use current transformers for all

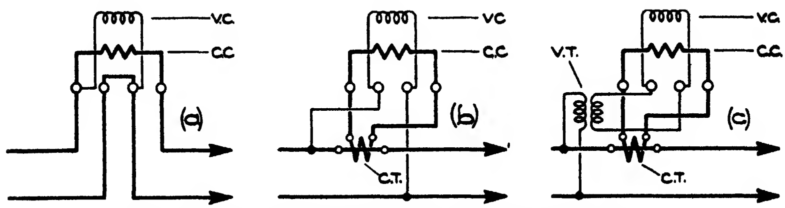


FIG. 21.—Connections for single-phase two-wire meter.

currents, irrespective of their magnitude, and a voltage transformer is used in the voltage circuit. The internal connections of the meter are the same as for a current-transformer-operated meter and the windings are arranged for 5 amperes, 110 volts. The diagram for a high-voltage meter is shown in Fig. 21 (c). Single-phase three-wire meters are connected as in Fig. 22 (a) and current-transformer-operated meters as in Fig. 22 (b).

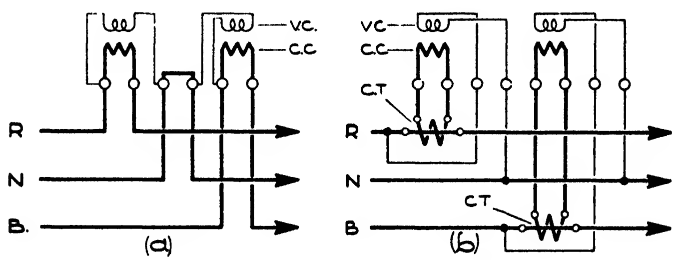


FIG. 22.—Connections for single-phase three-wire meter.

3.17. Standard Dimensions for Single-Phase Meters. At the request of a number of Associations representing the Supply Authorities in Britain, before the British Electricity Authority was formed, the meter manufacturers put forward proposals for the standardization of the external dimensions and the fixing centres of single-phase meters up to 50 amperes rating. These proposals were mutually agreed for commercial

credit-type single-phase meters and were added to the current edition of the British Standard for Electricity Meters as Amendment No. 1: June, 1946. They became mandatory for future designs as from January, 1948, but are optional in their application to meters already in production at that date. As a matter of fact, most meter manufacturers have modified the cases of meters in current production, to conform to the standard dimensions which are shown in Fig. 23.

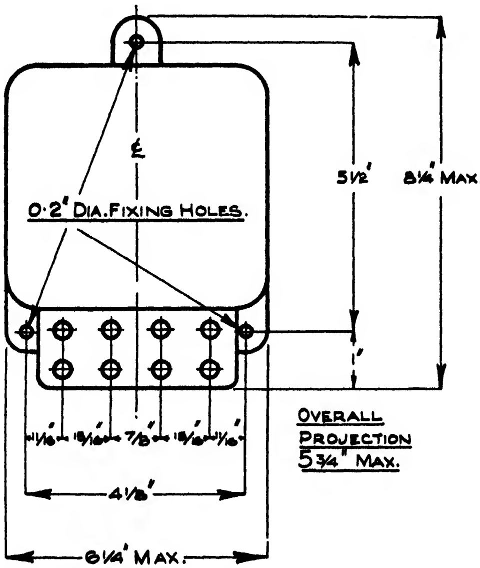


FIG. 23.—Standard dimentions for single-phase whole-current meters.

Owing to the diversity in the dimensions of the meter element as supplied by different manufacturers it was not possible to adopt one standard case. Accordingly, maximum dimensions are specified which must not be exceeded, but any manufacturer is at liberty to produce a meter smaller than these maxima. The terminal centres and their relationship to the fixing points of the meter are the same for all meters. The diameter of the holes in the terminals remains in accordance with the requirements of Clause 22 of B.S. 37: 1937 and is as follows:

¼ in. diameter in meters up to and including 25 amperes.
⅜ in. diameter in 50-ampere meters.
½ in. diameter in 100-ampere meters.
⅜ in. diameter permissible in 25-ampere long-range meters.

Consideration has been given to a proposal that all credit-type meters used in domestic consumers' premises should have one size of terminal hole, irrespective of the current rating, but the adoption of such a

FIG. 24.—Electrical Apparatus Co. single-phase meter.

proposal is likely to be deferred until a revision of the specification takes place.

3.18. Single-Phase Meters in Current Production. The number of firms engaged in the manufacture of single-phase meters in Britain is considerable and until the nationalization of the electric supply industry in 1948, the number of Supply Authorities purchasing meters was also

very large. Because of the diversity in the requirements of purchasers and the competition between the many manufacturers to satisfy these requirements, large-scale and economical production was rendered difficult. It may be that as a result of nationalization and the concentration of purchasing power amongst a smaller number of individuals, many of the unnecessary variations in design will tend to disappear. Such a tendency would undoubtedly be to the ultimate benefit of manufacturer and purchaser alike.

It is not possible in the space available to give a detailed description of the many single-phase meters in current production, and in the succeeding paragraphs a few representative types have been selected in

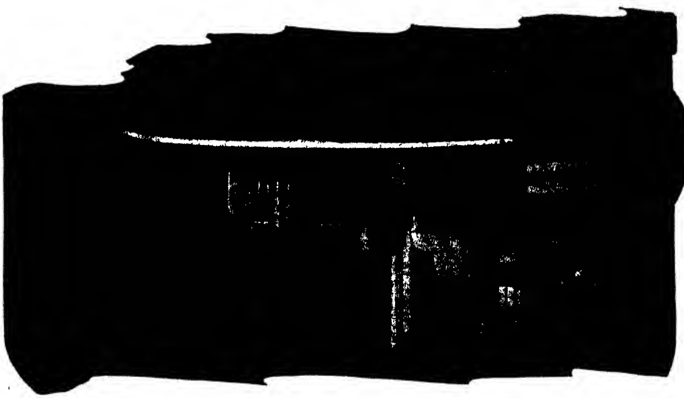


FIG. 25.—Magnet adjustment in E.A.C. single-phase meter.

order to illustrate some of the points of difference arising in practice.

3.19. Electrical Apparatus Co. Single-Phase Meter. The single-phase meter, Type E.H.D., manufactured by the Electrical Apparatus Co. Ltd., is shown in Fig. 24. The meter element is housed in a case of moulded insulating material, conforming to the limiting dimensions, fixing centres and terminal spacing laid down in Amendment No. 1 of B.S. 37: 1937. The carrying handle, which is not visible in the illustration, folds behind the meter-case when installed, and can be swung forward over a projecting fin to be seen on the top of the meter-cover. This device permits the cover to be held in position without the necessity for using the cover screws and is a convenience during calibration; all the fixing screws are inaccessible after the meter is installed and sealed.

The brake magnet of nickel-aluminium-cobalt steel is mounted on

a machined platform and requires no levelling devices. Two adjustments are provided for varying the speed on full load. The first—a coarse adjustment for use by the manufacturer, permits the magnet to swing around its centre fixing point, after which it is locked in position. The second—intended for use by the purchaser, consists of a pivoted piece of soft iron so shaped as to have a progressive diverting effect on the flux of the magnet as it approaches the magnet poles. The diverter is secured by a screw, and an engraved plate indicates its position. The marks on the plate are one-sixteenth of an inch apart

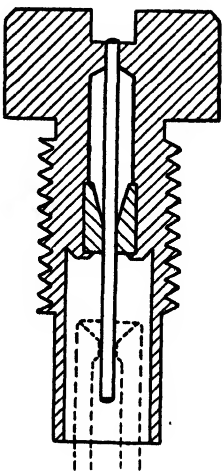


FIG. 26.—Top bearing in E.A.C. single-phase meter.

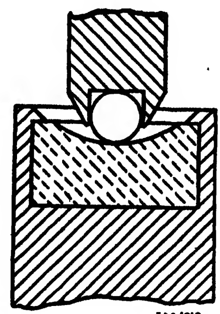


FIG. 27.—Bottom bearing in E.A.C. single-phase meter.

and represent approximately 0·4 per cent. speed variation per division; a total range of about 5 per cent. is provided on the fine adjustment and about 30 per cent. on the coarse. An illustration of the magnet and its adjustment appears in Fig. 25. The low-load adjustment is also visible in this figure to the left of the brake magnet and is adjusted in a similar manner. The inductive-load adjustment is operated by turning a screw, the head of which protrudes above the bracket carrying the register. The effect of turning the screw is to raise or lower a copper loop which surrounds the extremity of the centre pole of the voltage electromagnet.

The register is of the pointer type, and as may be seen in Fig. 24, the four main indices are unusually large, thus making for ease in

reading. It is secured by means of two finger clips and automatically meshes in the correct position when replaced after removal. Enlarged sectional views of the top and bottom bearings of the rotor are shown in Figs. 26 and 27. The top bearing consists of a screw, down the centre of which runs a steel wire possessing some degree of flexibility. The wire is secured at its upper extremity, and is supported midway by a bush through which the lower end of the wire projects. The top bearing cap

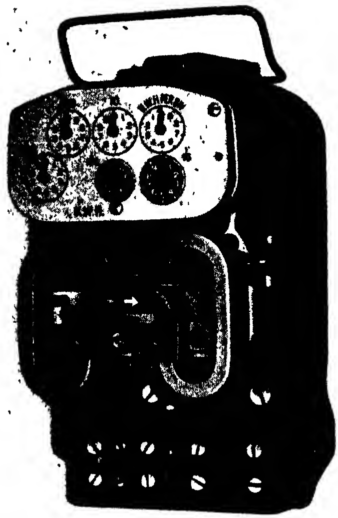


FIG. 28.—Metropolitan-Vickers single-phase meter.

of the rotor shaft is shown by dotted lines, inside the skirt on the lower end of the screw; the skirt protects the bearing from the ingress of dust and limits the amount of deflection to which the pivot can be subjected. The bottom bearing consists of a highly polished and hardened steel ball, pressed into the lower end of the rotor shaft and resting in a sapphire cup. The sapphire is set in a brass stem supported on a helical spring contained within the bottom bearing screw.

3.20. Metropolitan-Vickers Single-Phase Meter. The single-phase meter, Type N.E.I. manufactured by Metropolitan-Vickers Electrical Co., is shown in Fig. 28 with main cover and terminal cover removed. The meter is contained in a case of moulded insulating material and is secured to the meter board at three fixing points. The two lower fixing

screws are located, one on each side of the terminal block and when the meter is installed and the terminal cover is in position, the bottom fixings are inaccessible.

The voltage and current electromagnets are combined together and form a closed magnetic circuit as illustrated in Fig. 29. The whole is mounted on the meter frame and makes a rigid structure with a constant airgap between the two electromagnets. Freedom from interference

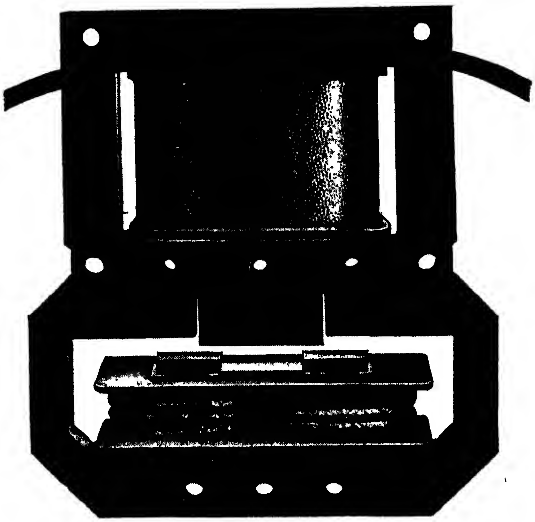


FIG. 29.—Electromagnet system in M.-V. single-phase meter.

by stray external magnetic fields is claimed for this arrangement. The brake-magnet system is shown in Fig. 30. Two tungsten-steel magnets are clamped to a plate and a magnetic shunt is mounted across the poles below the airgaps; the shunt is conveniently arranged for adjustment by turning the serrated disc below the magnet clamp. There are twenty serrations on the disc and the displacement of one division changes the speed of the rotor by 0·1 per cent. to 0·15 per cent., according to the position of the shunt. After adjustment, the shunt is locked by means of a clamping screw. In addition to this fine adjustment, a coarse adjustment may be obtained by moving the entire magnet system inwards or outwards. This is effected by screws in the magnet bracket, two being in tension and four in compression, and is intended for use as a factory adjustment.

The low-load adjustment consists of a metal loop which can be moved across the face of the voltage electromagnet pole. Movement of the loop is effected by turning a screwed stem having a four-armed head which is located above the rotor and to the right of the brake magnets. One complete turn of the head alters the speed on one-twentieth load by 2½ per cent. The inductive-load adjustment is made by moving a clamp along a resistance wire loop located behind the brake magnets and below the series electromagnet.

The rotor consists of an aluminium disc having a die-cast hub and is mounted on a light-alloy shaft with a pinion on its upper part; the

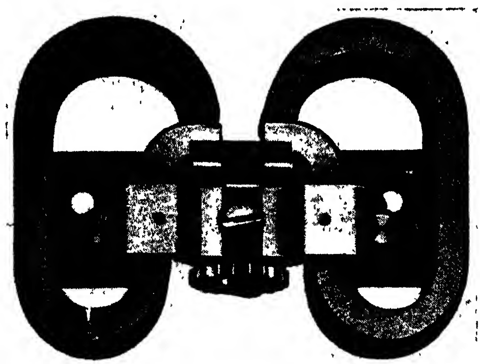


FIG. 30.—Brake-magnet system in M.-V. single-phase meter.

circumference of the disc is marked with a 100-division scale to facilitate stroboscopic testing. The top bearing consists of a polished steel pin moulded in a die-cast housing, which fits into a machined hole in the meter frame. The pin dips into an oil well in the top of the rotor shaft, and is sufficiently flexible to counteract any tendency to chatter.

The bottom pivot consists of a polished steel wire having a spherical end, and screwed into the lower end of the rotor shaft. It rests on a sapphire cup set in a brass mount, the latter being supported on a helical spring inside the jewel housing. The spring permits slight lateral movement in all directions in addition to slight vertical movement. Both top and bottom bearings are held securely in the meter frame by spring clamps and are instantly removable. A pinion cut on the upper end of the rotor shaft engages with the first wheel of the register; the latter is carried on two stems which fit into sockets in the meter frame. The stems are set so that when pushed right home,

correct meshing between the register and the pinion on the rotor shaft is ensured.

3.21. Chamberlain and Hookham Single-Phase Meter. The Chamberlain and Hookham single-phase meter, Type K, is housed in a case of moulded insulating material and is illustrated in Fig. 31. The overall

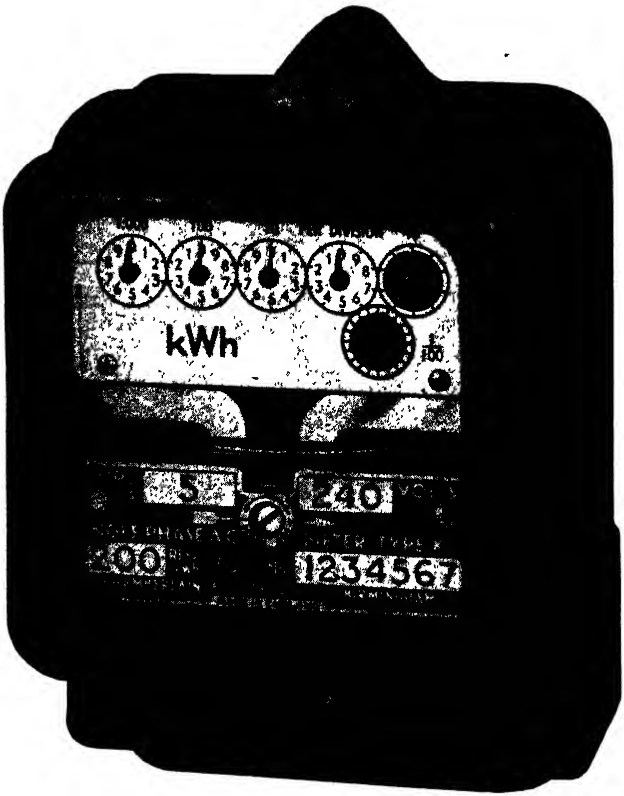


FIG. 31.—Chamberlain & Hookham single-phase meter.

dimensions, the fixing centres and the terminal spacings are in line with the dimensional standards for single-phase meters as laid down in addendum to B.S. 37: 1937, Amendment No. 1. After the meter is fixed and the terminal cover is in position, all the fixing screws are inaccessible. The carrying handle is hinged behind the terminal compartment, and the meter when being carried, is in an inverted position,

thus relieving the rotor pivot and jewel from shocks likely to cause damage to these parts.

The voltage and current electromagnets are mounted on an iron backplate and are dowelled so that if removed they can be replaced in

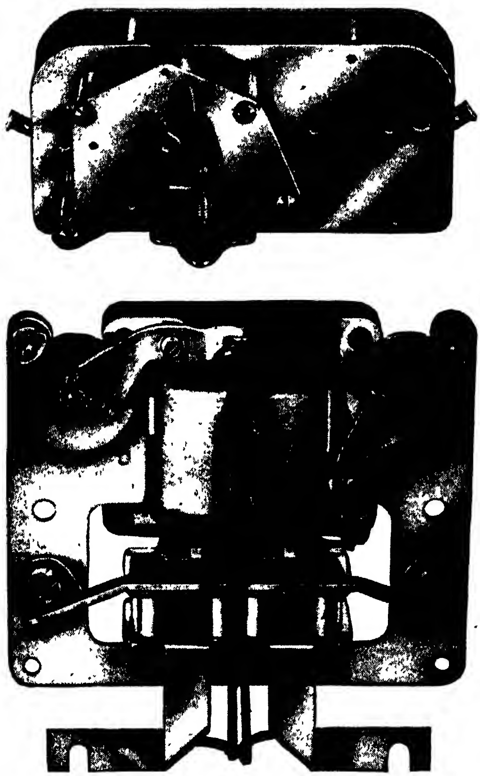


FIG. 32.—Low-load and inductive-load adjustments in C. & H. single-phase meter.

exactly the same position. The backplate complete with electromagnets, and low-load and inductive-load adjustments, is secured by two screws to the back of the meter case. A saturable magnetic shunt across the poles of the voltage electromagnet reduces the errors due to change of voltage to negligible proportions. A magnetic shunt across the poles of the current electromagnet reduces the error on heavy overloads, and nickel-steel alloy inserts improve the low-load performance.

A die-cast frame carries the brake magnets, the rotor with its top and bottom bearings, and the register. The frame is attached to the backplate by four fixing screws, and the heads of the two fixing screws which secure the backplate to the meter case act as dowels to locate the rotor accurately with reference to the airgap between the electromagnets. Thus, the frame can be removed should this be desired to give access to the electromagnets, and can be replaced without disturbing the calibration.

Two powerful cobalt-steel brake magnets are provided, and are carried between two stout brass plates which form a complete unit for attachment to the die-cast frame. A magnetic shunt located between the magnet poles below the disc can be moved by means of a micrometer screw, and this serves as the main adjustment for full load. Due to the shape of the shunt, a substantially straight-line adjustment of one per cent. per turn of the screw is achieved. Pole tips of a temperature-sensitive material provide temperature correction for all loads at unity power-factor.

A rear view of the low-load and inductive-load adjustments may be seen in Fig. 32. The low-load adjustment seen on the right of the illustration, consists of a toothed sector engaged by a pinion which, when turned, causes a lateral movement of a metal screen surrounding the tip of the middle limb of the voltage electromagnet. Similarly, the inductive-load adjustment seen on the left of the illustration consists of a toothed sector engaged by a pinion which, when turned, raises or lowers a copper screen in the side-gaps of the voltage electromagnet. Each of these pinions is mounted on a disc revolving on a peg, and is driven through a friction device operable from the front of the backplate by means of a slotted head which can be turned with a screwdriver. When the adjustment reaches the end of its travel, further turning of the slotted head permits slip between the friction device and the edge of the disc, and no damage can result from overturning. All adjustments are accessible from the front of the meter and are self-locking; all are operable by means of a screwdriver and, in each case, clockwise movement increases the speed of the meter.

A sectional view of the rotor shaft and its bearings is shown in Fig. 33. Both top and bottom bearings are sprung into sleeves fitted in the die-cast frame. They can readily be withdrawn by finger and thumb, and when replaced slip back into the correct position. The top pivot consists of a highly-polished springy steel wire which dips into an oil recepticle in the top of the rotor shaft. A skirt surrounding the

top of the shaft prevents undue deflection of the pivot under any condition. The bottom pivot consists of a hardened steel wire with a highly-polished ball point and is fitted into a stem which screws into the lower part of the rotor shaft. When screwed home, two conical surfaces ensure correct centring of the pivot. The pivot rests on a sapphire cup which is set in a brass plug and is supported on a spring inside the jewel housing. By removing a screw, the sapphire can be withdrawn for inspection and if necessary can be replaced by a new one.

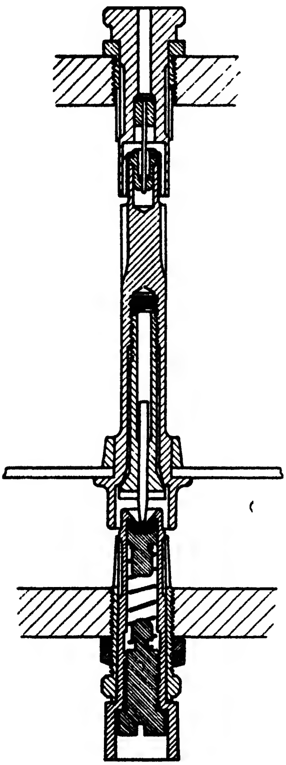


FIG. 33.—Sectional view of rotor and bearings in C. & H. single-phase meter.

3.22. Siemens Single-Phase Meter. The single-phase meter, Type 23, manufactured by Siemens Bros. and Co. Ltd., is shown in Fig. 34 with main cover and terminal cover removed. The meter is contained in a case of moulded insulating material and conforms to the limiting dimensions, fixing centres, and terminal spacings as laid down in Amendment No. 1 to B.S. 37: 1937. The carrying handle at the top of the meter is arranged, when drawn forward, to hold the cover in position without the use of the cover fixing screws. The disconnecting device for separating the voltage circuit from the current winding may be seen above the "Line" terminals. By slackening off the left-hand screw passing through the plate, the voltage terminal is isolated from the current terminal and a test lead may then be secured by the right-hand screw; when installed and sealed, all the meter-fixing screws are inaccessible.

The current and voltage electromagnets together with the low-load and inductive-load adjusting devices are secured to an iron mounting plate which forms part of the magnetic circuit, and this is fixed in the back of the meter case by two screws. Both electromagnets are dowelled in position to ensure correct location, should these be removed and

replaced at any time. A die-cast frame carries two brake magnets of nickel-aluminium-cobalt steel, together with a magnetic shunt for the full-load adjustment. The rotor together with its top and bottom bearings, and the register with its supporting bracket, are also mounted on the frame. The whole of this assembly is then screwed to the iron mounting plate.

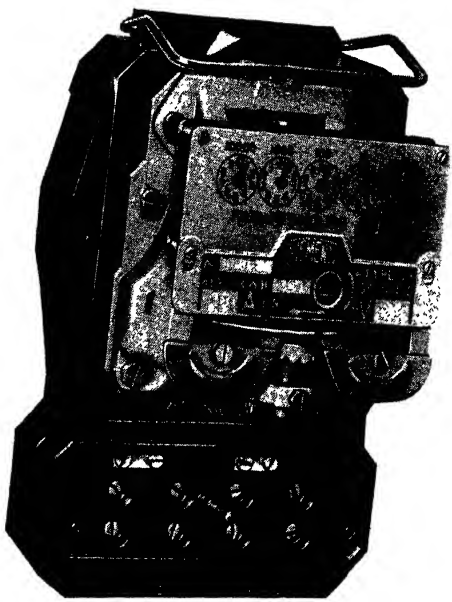


FIG. 34.—Siemens Bros. single-phase meter.

The full-load adjustment which may be seen in Fig. 34, consists of a flanged iron disc attached to a micrometer screw, and mounted below the rotor between the poles of the brake magnets. The micrometer screw may be raised or lowered, and after adjustment may be clamped to prevent further movement. The low-load adjustment consists of a sector-shaped metal plate, shown by the dotted line in Fig. 35. This plate can be swung from side to side, across the face of the voltage electromagnet poles, and is operated by means of a worm and worm-wheel arrangement. The elongated screw head, attached to the worm portion, is

visible through a hole in the nameplate and may be seen in Fig. 34. The inductive-load adjustment seen in Fig. 35, consists of a copper loop embracing the centre pole of the voltage electromagnet. This loop can be raised or lowered by turning a micrometer screw in a bracket on the top limb of the electromagnet; the thread of the screw engages with an indented plate, the lower end of which is attached to the loop.

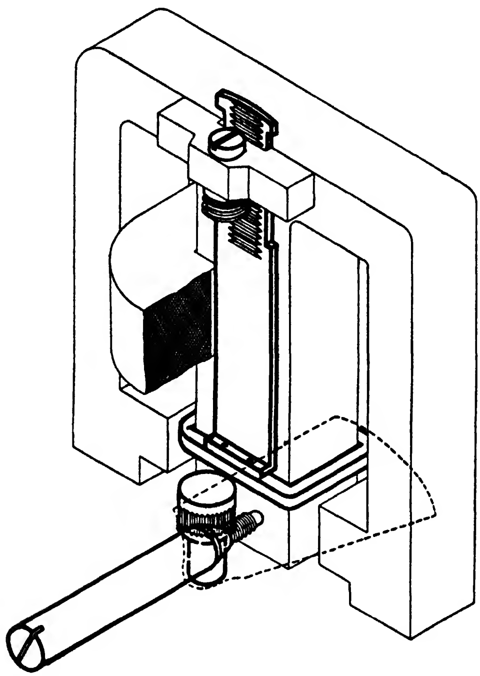


FIG. 35.—Low-load and inductive-load adjustments in Siemens single-phase meter.

The top bearing consists of a polished steel pin secured in the top bearing screw by white metal and projecting into a hole in the top of the rotor shaft. The bottom bearing shown in Fig. 36, consists of a polished steel ball resting in a sapphire cup; the ball is secured in the end of a brass plug making a sliding fit inside a hollow cylinder which is inserted in the hub of the rotor. Behind the plug and inside the cylinder is a spring which forms a resilient support between the ball and the rotor. This construction is a departure from the more usual

arrangement in which the spring support for the rotor is located below the sapphire cup in the bottom bearing screw. The register is carried by a bracket having forked ends which spring open after entry into slots in the backplate. The first driven wheel meshes

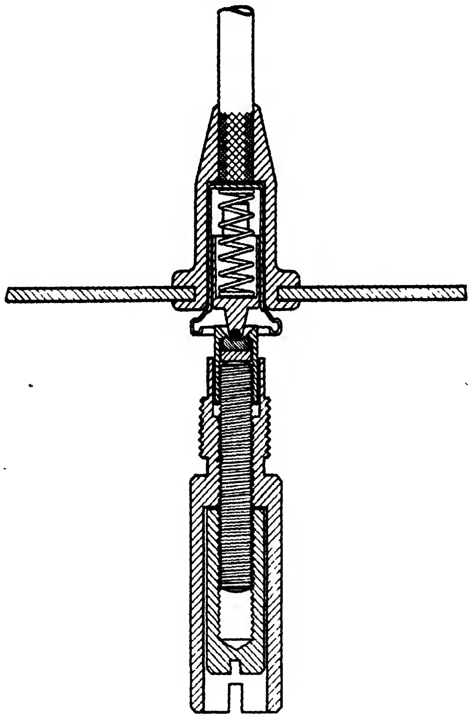


FIG. 36.—Bottom pivot and jewel in Siemens single-phase meter.

automatically in the correct position with the driving pinion carried on the top of the rotor shaft.

3.23. Measurement Single-Phase Meter. The single-phase meter, Type Z.F. manufactured by Measurement Ltd., is illustrated in Fig. 37, which shows the meter with the main cover, terminal cover and register removed. It is enclosed in a case of moulded insulating material, and when installed on consumers' premises and sealed the three fixing screws are inaccessible. The carrying handle which is at the top, folds

behind the case when not in use. A view from the side with some of the parts in section is shown in Fig. 38.

A novel feature in this meter is the brake magnet system; a small "U"-shaped permanent magnet is located below the rotor, and presents

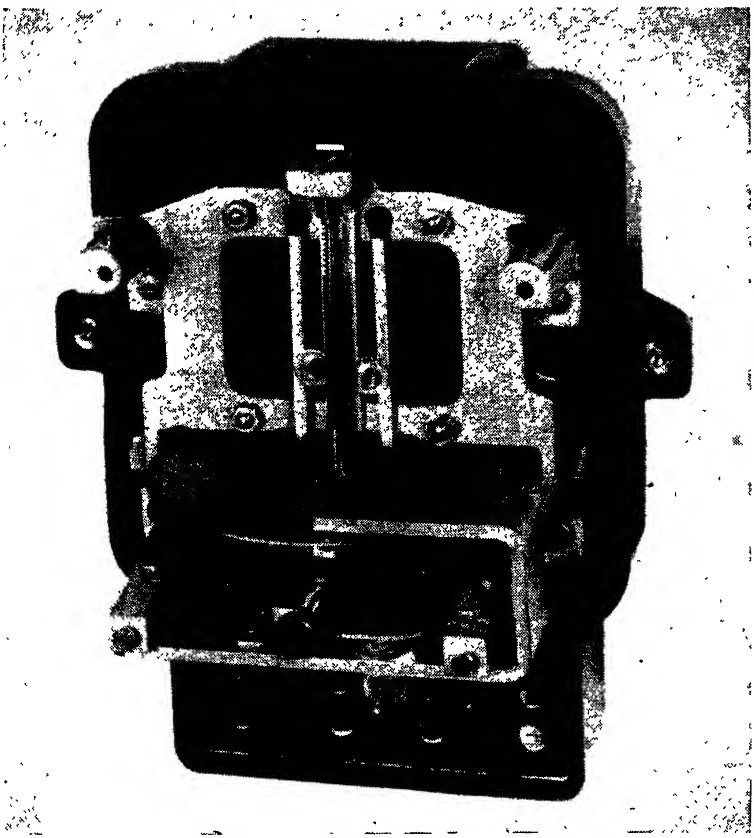


FIG. 37.—Measurement Ltd., single-phase meter.

its polar faces to the underside of the disc. The magnet rests on a mild-steel strip which is extended over the upper side of the disc immediately above the magnet poles as shown in Fig. 37. The flux from the permanent magnet cuts twice through the disc, the upper extremity of the steel strip forming part of the magnetic circuit; the magnet is capable of

rotation about a vertical axis, and this feature permits the brake force to be adjusted.

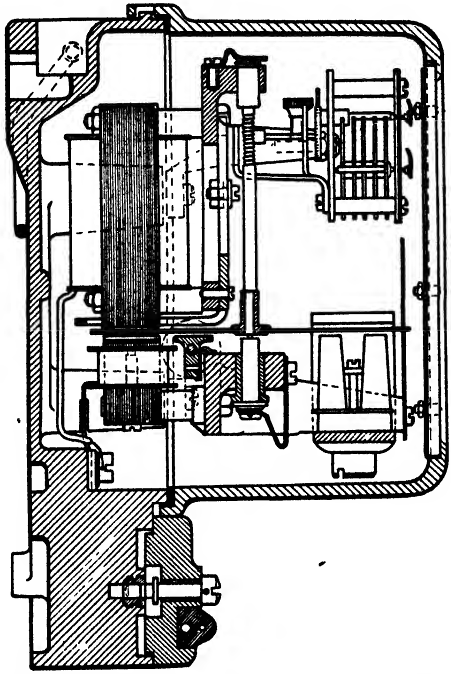


FIG. 38.—Side view of Measurement single-phase meter.

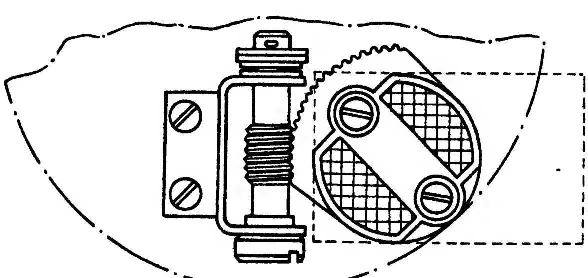


FIG. 39.—Brake-magnet adjustment in Measurement single-phase meter.

A plan of the brake magnet and its adjusting device in relation to the disc, is shown in Fig. 39, the pole faces being indicated by cross

hatching. A toothed sector attached to the base of the magnet is engaged by a worm mounted in a bracket. A slotted head on the worm spindle enables a screwdriver to be used for the purpose of rotating through a limited arc, the sector and the magnet to which it is secured. The position of the magnet in Fig. 39 is that in which the greatest

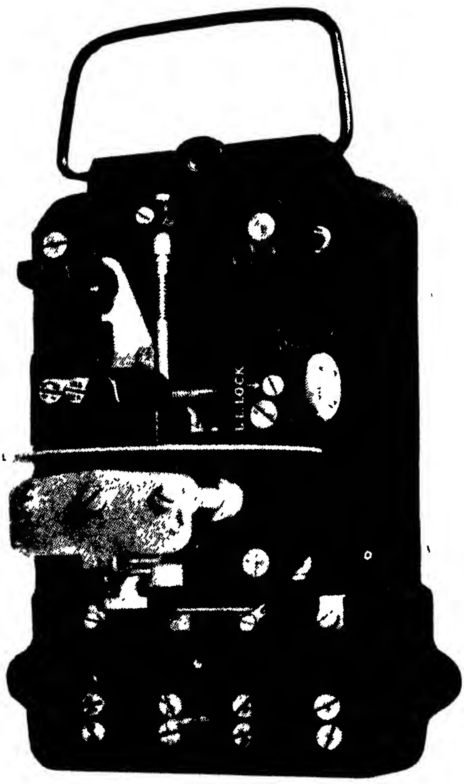


FIG. 40.—Ferranti single-phase meter, interior.

brake force is exerted. Rotation of the magnet on its axis in an anti-clockwise direction will reduce the brake force and increase the speed of the rotor.

The material of which the magnet is constructed is an alloy of titanium, nickel, aluminium, and cobalt, and is known by the trade name of "Ticonal". The constituents in powder form are inserted in a

die and are subjected to very heavy pressure which solidifies the mass. During subsequent heat-treatment and cooling, a strong magnetic field is applied along the preferred magnetic axis. The final magnetization along the same axis produces a very powerful magnet having the remarkably high coercive force of 740 units, which ensures that demagnetization by any forces likely to be experienced in the meter will have negligible effect.

The quadrature loop in the Measurement meter is a fixture, and the inductive-load adjustment is made by varying a resistance in series with the loop. This is accomplished by altering the position of two clamps, which form bridges between a strip of resistance material lying parallel to extensions of the loop; the adjustable portion may be seen in Fig. 37 immediately behind the rotor shaft. Raising the clamps reduces the speed of the rotor on inductive loads. The low-load adjustment is made by moving an iron block located below the rotor disc in the region of the centre pole of the voltage electromagnet. This movement disturbes the symmetry of the voltage flux passing through the disc, and is effected by turning a knurled screw head located to the right of, and immediately below the disc, as seen in Fig. 37. Clockwise rotation of the screw head increases the rotor speed on low loads.

3.24. Ferranti Single-Phase Meter. The single-phase meter Type F.M., recently introduced by Ferranti Ltd., supersedes the well-known Type F.L. hitherto supplied. An interior view of the meter, with the main cover, terminal cover and register removed, is shown in Fig. 40. The case is of moulded insulating material and conforms to the limiting dimensions, fixing centres and terminal spacing laid down in Amendment No. 1 to B.S. 37: 1937.

The meter element consists of a cast-iron frame behind which the voltage and current electromagnets are secured. The braking system, the register, and all the adjusting devices, are mounted on the front of the frame. The rotor, consisting of an aluminium disc mounted on a light alloy spindle, has 150 equally spaced divisions around its periphery for the purpose of stroboscopic testing. A worm cut in the upper portion of the spindle drives the register through a worm wheel. The register has six indices and is made entirely of light alloy. All the parts are anodised, the moving parts being of a different grade of metal from that of the plates in order to minimize friction and maintain good performance without oiling. The makers claim that the friction level is lower than that of a combination of most other dissimilar metals and that the friction level does not increase with age.

The top and bottom bearings for the rotor are shown in Figs. 41(a) and 41(b) respectively. The top bearing sleeve carries a flexible steel pin which enters a pivot hole in a removable cap fitted on the top of the rotor spindle. A skirt on the sleeve surrounds the cap and prevents damage to the pin. The bottom bearing consists of a removable hardened steel pivot fitted in the lower end of the rotor spindle and

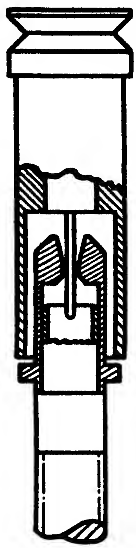


FIG. 41 (a).—Top bearing in Ferranti single-phase meter.

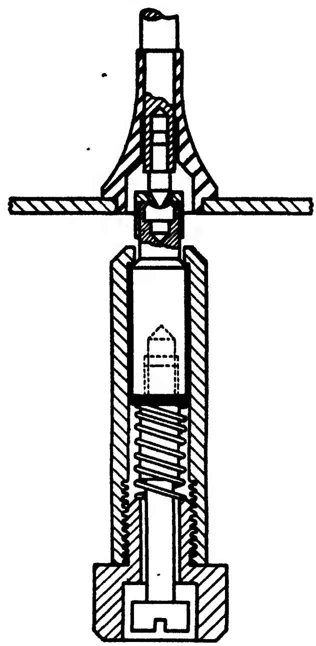


FIG. 41 (b).—Bottom bearing in Ferranti single-phase meter.

resting on a synthetic sapphire cup. This cup is mounted in a detachable unit supported on a spring and housed in a screwed sleeve which may be adjusted for height and then locked in position. A change of jewel does not alter the height of the rotor in the magnet gaps, and the jewel mounting is self-centring when replaced.

The brake magnet is "U"-shaped and is located with its pole pieces in close proximity to the underside of the disc. It is supported on two pillars along which it can be traversed radially with respect to the disc for the purpose of adjustment. The magnetic circuit is completed above

the disc through a soft iron piece secured to the meter frame, thus providing two well-defined flux paths through the disc. The material of which the magnet is composed is an alloy having a very high remanence and is subjected to pre-magnetization during heat-treatment. The subsequent magnetization ensures a powerful magnet with a high degree of stability.

The current electromagnet is built up from "U"-shaped laminations upon which a former wound coil is secured and the complete assembly is shown in Fig. 42. A magnetic shunt between the inner pole tips saturates at the higher loads and ensures a good performance on the upper part of the load curve. Changes in registration due to changes in

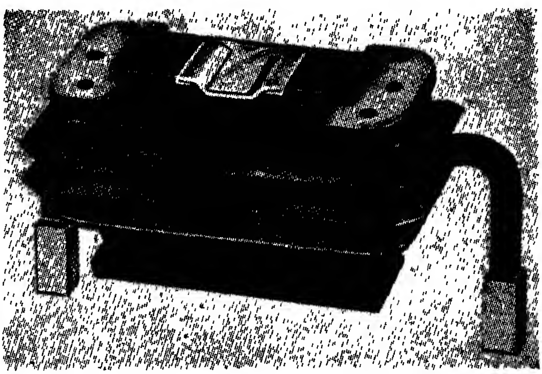


FIG. 42.—Current electromagnet in Ferranti single-phase meter.

ambient temperature are reduced to small proportions by the incorporation of permeability-temperature sensitive material adjacent to the poles of the current electromagnet.

The low-load adjustment consists of a steel block mounted on the middle pole-piece of the voltage electromagnet. By turning the knurled head seen on the extreme right of the frame in Fig. 40, this block can be moved so as to produce a dissymmetry of the voltage leakage flux, which in turn produces a small driving force sufficient to overcome the frictional retardation. The inductive-load adjustment consists of a copper loop surrounding the middle pole of the voltage electromagnet, combined with a rack and pinion for raising or lowering the loop in the gap which carries the main voltage flux. All adjustments are provided with locking devices.

CHAPTER IV

SINGLE-PHASE METERS: THEORY AND PERFORMANCE

4.1. Theory of Induction Meter. In the previous chapter the elements of a single-phase induction type meter have been described. A voltage electromagnet comprising a laminated iron core having a nearly closed magnetic circuit and a coil of many turns of fine wire, is located on one side of the rotor, usually the upper side. The voltage coil is highly inductive and the small current which it carries, lags approximately 85 deg. behind the voltage of the supply to which it is connected. The

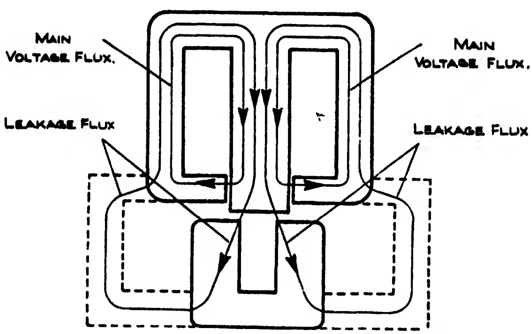


FIG. 43 (a).—Path of voltage flux in driving element.

magnetic flux due to the voltage coil, which will be called the voltage flux, is in phase with this current and consequently, also lags about 85 deg. behind the supply voltage. The phase compensating loop fitted on the lower portion of the middle limb and shown in Fig. 14 (page 48) increases the lag of the leakage flux to 90 deg. This loop is made adjustable in a vertical direction and is commonly referred to as the quadrature band, or the quad band for short.

The path followed by the voltage flux at the instant when no current is passing through the current coils of the meter is shown in Fig. 43 (a). It will be noted that the leakage flux crosses the airgap between the poles of the voltage and current electromagnets, dividing equally between the two poles of the current electromagnet and returning to the voltage electromagnet through paths which are enclosed in dotted

lines. In some meters, these return paths form part of the laminated structure of the electromagnets, but in others the electromagnets are separate units and are joined together magnetically by mounting on a cast-iron or pressed-steel framework. Since the leakage flux is only a small proportion of the total voltage flux, the iron losses in the return path are relatively insignificant and the use of cast-iron for this purpose offers no serious disadvantage from the magnetic standpoint.

The current electromagnet consists of a ⊔-shaped laminated iron core, mounted below the rotor and disposed symmetrically with respect to the voltage electromagnet. It is wound with a few turns of

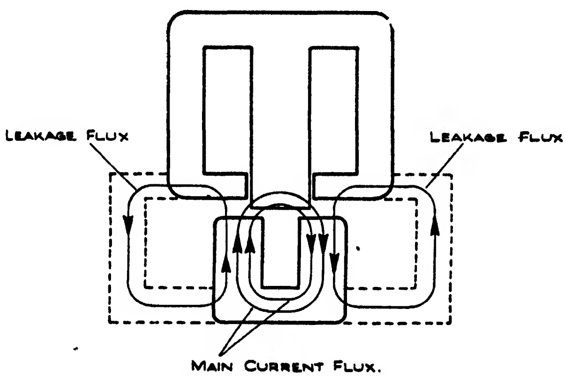


FIG. 43 (b).—Path of current flux in driving element.

heavy gauge wire and carries the total current to be metered, except in the case of meters connected to current transformers, in which case it carries the secondary current. The flux due to the current winding is in phase with the current producing it and consequently when the load on the circuit is non-inductive, the current flux is in phase with the supply voltage. The path of the current flux is shown in Fig. 43 (b) at the instant when there is no voltage flux in the airgap between the two electromagnets. Under this condition the current flux cuts twice through the rotor, once in the upward direction and once in the downward, as shown by the arrows. At any other instant when the voltage flux is also crossing the airgap, the combination of the two fluxes results in a strengthening of one pole and a weakening of the other, since the voltage flux across the gap at any given instant is unidirectional. There is a leakage flux from the current electromagnet as shown by the lines

traversing the return paths but this is so small as to be relatively insignificant.

The phase relationship between the voltage and current fluxes when the load is non-inductive and the power-factor is unity is shown graphically in Fig. 44. Starting from the instant when the supply voltage and the current in the main circuit are passing through zero value, both increase in unison and reach a maximum value in the positive direction one-quarter of a cycle later as shown at (*a*). At half a cycle from the start, both have decreased and are passing through zero value as shown at (*b*), while at (*c*), three-quarters of a cycle from the start, both have

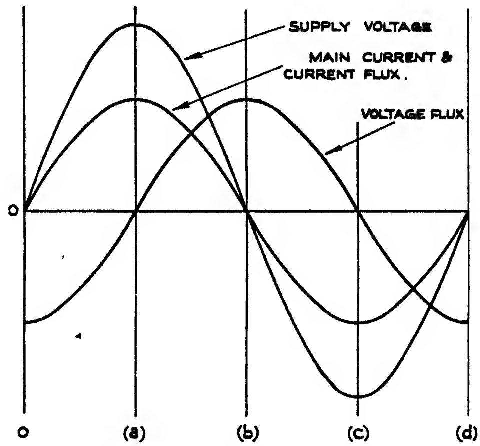


FIG. 44.—Phase of voltage and current fluxes at unity power-factor.

reached a maximum value in the negative direction. At (*d*) the cycle is complete and both are again passing through zero. The current flux is in phase with the current in the main circuit but the voltage flux lags 90 deg. behind the supply voltage as previously explained: there is in consequence a phase difference of 90 deg. between the voltage and current fluxes.

Bearing in mind these relationships it is now possible to explain why the disc rotates. In Fig. 45, four views on the left are shown, looking down on the rotor disc, of the direction of the induced currents in the disc, due to the changing fluxes in the poles of the voltage and current electromagnets. On the right of the figure, the poles are shown as viewed from the front of the meter. The induced currents in the

disc attain their maximum values at the instant when the fluxes producing them are changing at the maximum rate. This instant coincides with the change from a positive to a negative value, or vice versa, as the flux passes through zero. At the instant when the respective fluxes attain their maximum values, the rate of change of flux is zero and consequently the induced currents in the disc are likewise zero. At the

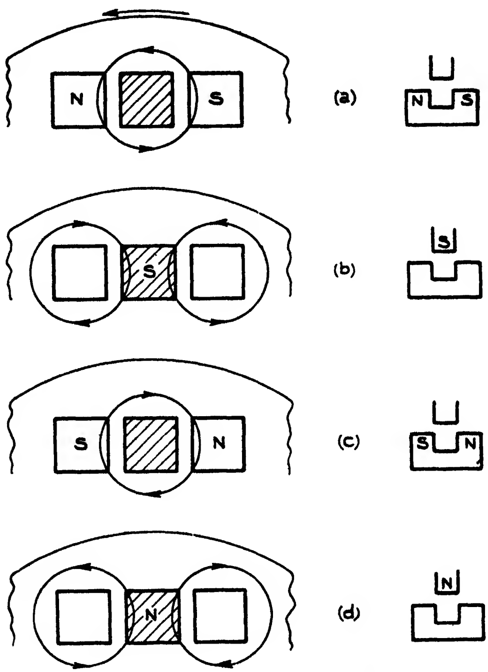


FIG. 45.—Currents induced in rotor-disc by driving elements.

instant indicated at (*a*) in Fig. 45 which corresponds to (*a*) in Fig. 44, the voltage flux is passing through zero and changing at the maximum rate. The voltage electromagnet at this instant exhibits no polarity, but the induced current in the disc beneath the voltage pole is circulating in an anti-clockwise direction as indicated by the arrows. At the same instant the main current and the current flux have reached a maximum value and the current electromagnet exhibits a north pole on the left and a south pole on the right. The direction of the induced current in

the disc in the region of these poles is such as to cause this portion of the disc to move from right to left; the front portion of the disc which is nearest to the observer will therefore move from left to right as is standard practice in all meters made in this country.

At the instant indicated at (*b*) the voltage flux has reached its maximum value and its rate of change is zero. The voltage electromagnet exhibits a south pole to the disc but no current is being induced in the disc thereby. The main current and the current flux on the other hand are passing through zero value and consequently the current electromagnet exhibits no polarity. The rate of change of current flux is at a maximum value and induced currents circulate around each current pole in opposite directions as shown by the arrows on the circles. These induced currents reacting with the south pole presented by the voltage electromagnet, cause this portion of the disc to move from right to left. At the instants indicated at (*c*) and (*d*), similar reactions occur, and if the flux relationships at intermediate points are analysed, it will also be found that the portion of the disc in the region of the electromagnets is urged in the direction from right to left.

4.2. Vector Diagram for Induction Meter. The voltage coil of an induction meter is fitted on a nearly closed magnetic circuit and is highly inductive. In the ideal meter, the current taken by the coil would be exactly 90 deg. behind the applied voltage, and the voltage flux acting on the disc would be in phase with this exciting current. In practice this ideal cannot be realized, partly because the resistance of the voltage coil reduces the current lag and partly because of the eddy current and hysteresis losses in the core of the electromagnet. It is usual to keep down the iron losses by working at a moderate magnetic induction in the core, by the use of alloy steel having low losses, or by using thin laminations to reduce eddy current losses. As regards the voltage coil, the resistance is kept as low as possible for the required number of turns by winding with wire of the largest section that can be accommodated in the available space.

In the average induction meter the discrepancy between the actual 85 deg. and the necessary 90 deg. is made good by means of a quadrature-adjusting device usually fitted on that part of the electromagnet pole carrying the leakage flux. This device which has already been referred to as the quad band, consists of a closed loop of copper, brass or aluminium, capable of adjustment for position on or near the lower extremity of the middle limb as shown in Fig. 14 (page 48). The alternating flux which is linked with the quad band induces a voltage in the

latter, lagging 90 deg. behind the flux. By moving the quad band from the lower extremity of the pole to a position nearer to the voltage coil, the flux linkage can be increased with a corresponding increase in the induced voltage. The current resulting from the induced voltage in the closed loop will depend upon the resistance and reactance of the loop. The resistance is determined by the sectional area and length of the circuit and manufacturers provide a selection of quad

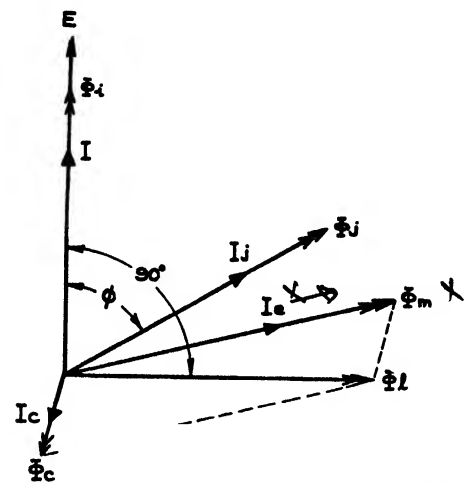


FIG. 46.—Phase relationship of fluxes in single-phase meter.

E	= Supply Voltage.	Φ_c	= Flux due to quad band.
I	= Main Current N.I.L.	Φ_i	= Flux due to current electromagnet (N.I.L.).
I_c	= Current in quad band.	Φ_j	= Flux due to current electromagnet (I.L.).
I_e	= Current in volt coil.	Φ_l	= Leakage flux due to voltage electromagnet.
I_j	= Main current I.L.	Φ_m	= Main flux due to voltage electromagnet.

ϕ = Phase displacement between supply voltage and main current.

bands to cover any adjustment which may be necessary. The reactance will vary with the position of the quad band and will affect the phase displacement of the induced current. This latter will always lag behind the voltage induced in the loop and consequently will lag more than 90 deg. behind the voltage flux. The magnetic field due to the current in the quad band lags behind the voltage flux and the resultant of the two fluxes in a correctly-adjusted meter will be 90 deg. behind the applied voltage.

The vector diagram in Fig. 46 shows the phase relationship between

these quantities. The voltage applied to the terminals of the voltage coil is indicated by the vector E and the exciting current in the voltage coil by I_e. The main flux in the core of the voltage electromagnet is in phase with the exciting current and is represented by Φ_m lagging less than 90 deg. behind E. The voltage induced in the quad band lags 90 deg. behind the flux Φ_m but owing to the impedance of this circuit the current lags behind the voltage and is represented by I_c. The flux set up by I_c is Φ_c and the resultant of Φ_c and Φ_m is Φ_l which is lagging 90 deg. behind E. It will be seen that by increasing or decreasing Φ_c as can be accomplished by varying the position of the quad band, the phase displacement of Φ_l with reference to E can be adjusted to the desired value. The current in the exciting coil of the current electromagnet when the power-factor of the load is unity, is represented by the vector I and the resulting flux by Φ_i in phase with I. When the load is inductive the current is represented by I_j and the current flux by Φ_j. The angle ϕ is the phase difference between voltage and current in the main circuit and $\cos \phi$ is the power-factor of the load. The power in the circuit when the power-factor is unity is proportional to EI and when the load is inductive is proportional to $EI_j \cos \phi$.

4.3. Classification of Single-Phase Meters. The ideal single-phase induction meter would have an error curve showing zero error from the smallest load up to the maximum which the meter was capable of carrying continuously, under conditions which included the normal variations of voltage, frequency, power-factor, waveform, temperature, stray magnetic fields and vibration. In addition to these factors which concern performance, the meter would be capable of maintaining its initial accuracy over a period of years, easy to adjust, light in weight, reasonably small in size and lastly, but not least, moderate in price. No meter yet made incorporates all these desirable features, but many meters achieve a remarkable degree of accuracy under a variety of disturbing conditions and from the point of view of cost, compare favourably in value with any other commercially-produced article. In Great Britain, two grades of single-phase meter are recognized, namely "Commercial Grade" and "Precision Grade". The former is used in large numbers for the purpose of measuring electrical energy supplied to ordinary consumers and the latter grade is used mainly in test-rooms and laboratories for checking the accuracy of meters under test.

Commercial Grade meters are divided into two classes according to the range over which accurate measurements can be made. The first class concerns meters in which the makers' guarantee of accuracy is

confined to loads between 5 per cent. and 125 per cent. of rated current. This class includes all single-phase meters used in conjunction with current transformers, whole-current meters of 100 amperes rating and some meters of 50 amperes rating. The second class concerns "long-range" meters which are whole-current single-phase meters having an accuracy as specified in Clause 37 of Specification, B.S. 37: 1937. Most Commercial Grade meters up to and including 25 amperes rating now made in this country, are of the long-range variety. Precision Grade meters do not come in this category, nor in fact is this necessary or desirable, since the conditions under which they are used are such that only a limited range of loadings is required.

4.4. Limits of Error for Single-Phase Meters. Reference has already been made on page 4 to the Statutory Limits of Error and to the fact that the legal requirements do not take into account the practical limitations which militate against their achievement. The instruction requires that a meter shall register within the prescribed limits at any load at which it may be operating and if this is to be interpreted literally, it signifies that no matter how large or how small the load may be, whether variations in voltage, frequency, power-factor, temperature, waveform or any other disturbing factor be present to an abnormal extent, the meter must nevertheless register within the Statutory Limits. As every experienced meter engineer is well aware, no alternating-current meter can be accurate from zero load up to its maximum rating, nor can it be entirely free from errors arising from abnormal variations in service conditions. It is true, however, to say that in practice the combination of circumstances which would result in a normally accurate meter exceeding the Statutory Limits of error is unlikely to arise and consequently no importance need be attached to the implications in the Statutory Limits.

From a practical point of view, the British Standard for Electricity Meters, B.S. 37: 1937 (current at the time this book was prepared), may be regarded as laying down reasonable conditions to which a meter must conform. This standard is revised from time to time as circumstances warrant, and its conditions are generally acceptable to all supply authorities. The limits of error for alternating-current meters are defined in Clause 37 of B.S. 37: 1937, which states: "The error of the meter at the standard or marked temperature, voltage and frequency shall not exceed the values in the following Table:

"Where a range of voltage is marked on the nameplate, the requirements of this clause shall be satisfied at all voltages within the range.

TABLE 2

Limits of Error for Alternating Current Meters at Standard or Marked Temperature, Voltage and Frequency

Conditions of Test		Limits of Error		
Current expressed as a percentage of the Marked Current	Power Factor	Commercial Grade		Precision Grade
		Long Range	Normal Range	
		+ or −	+ or −	+ or −
200% to 125%	1·0	2·0 %	—	—
125% to 20%	1·0	2·0 %	2·0 %	0·5 %
At 10%	1·0	2·0 %	2·0 %	1·0 %
At 5%	1·0	2·0 %	2·0 %	1·5 %
200% to 125%	0·5 (lag)	2·5 %	—	—
125% to 20%	0·5 (lag)	2·0 %	2·0 %	1·0 %
At 10%	0·5 (lag)	2·5 %	2·5 %	2·0 %

A meter which is constructed for loads in excess of 125 per cent. of marked current and is distinctly marked as Long Range, shall comply with the provisions of this clause for Commercial Grade meters. For Precision Grade meters, there shall be permissible, a tolerance of 0·25 per cent. for meters for permanent installation and 0·5 per cent. for meters for portable use (e.g. as Substandards), which may be applied in one direction only for all the above conditions of test, i.e. a plus tolerance or a minus tolerance, but not both, the overall range of error remaining unchanged. Contacting and other mechanical auxiliary devices shall not be permissible on portable precision grade meters.

"When current transformers or voltage transformers are employed with meters, the error of the combination shall not exceed the values stated above. This condition must also be fulfilled should auxiliary apparatus be electrically connected.

"When a maximum-demand indicator or contacting or other auxiliary device is operated mechanically by the meter, the limits of error for 5 per cent. marked current at 1·0 power-factor, or 10 per cent. at 0·5 power-factor (lag) shall be subject to an allowable increase of − 2·0 per cent., and in the case of prepayment mechanisms so operated,

the limits under the same conditions shall be subject to an allowable increase of ± 1·0 per cent."

The limits of error detailed in the foregoing Table are applicable to meters operating under conditions of normal voltage, frequency and temperature. If any or all of these conditions become abnormal, or if other disturbing factors are introduced, the error of the meter may be subject to a change which may tend to increase or to cancel out the normal meter error. It is desirable in these circumstances to impose limitations to the permissible changes in the normal error, or alternatively to fix limits to the total error under abnormal conditions. A number of clauses have been introduced into B.S. 37: 1937, to cover such contingencies and consideration may now be given to these.

4.5. Permissible Errors due to Change in Voltage. Voltage errors may be divided into two categories, (1) those arising from the normal variations in the supply voltage and (2) those arising due to the voltage being abnormally high or low. Clause 38 in B.S. 37: 1937 deals with variation in error due to change in voltage and states: "If a meter has a voltage circuit, a variation of 10 per cent., in the case of A.C. meters, above or below the marked voltage, at any load from full to one-tenth at unity power-factor, shall not cause a change in the error of the meter in respect of such variation, of more than one per cent. When a range of voltage is marked on the nameplate of a meter, the requirements of this clause shall apply to all the voltages within the range."

Clause 44 deals with excess voltage and states: "The meter shall not be injured and its accuracy shall not be permanently impaired by the application of a voltage 25 per cent. above the marked voltage for a period of half-an-hour. The test for impaired accuracy shall be made not less than two hours after the completion of the excess voltage test, and the accuracy of the meter shall be regarded as not permanently impaired if the difference between the errors observed before and after the application of the excess voltage test does not exceed ± 0·5 per cent."

4.6. Permissible Errors due to Change in Frequency. The standard frequency in Great Britain is 50 cycles per second and as this frequency is normally controlled within very close limits,* the possibility of errors arising due to variation in frequency is very remote. Nevertheless a limitation to the possible error due to change in frequency is

* At the present time, owing to acute shortage of generating plant and consequent overloading, it is not possible to maintain frequency within the usual close limits. It is to be anticipated that this undesirable state of affairs will be overcome within the next few years.

desirable in the case of meters exported to countries where frequency control is not so rigid. Furthermore, a meter which is insensitive to change of frequency is usually unaffected by change of waveform and since tests to determine the effect of waveform are difficult to specify with precision, a clause dealing with errors due to variation in frequency does serve a useful purpose. Clause 42 in B.S. 37: 1937 stipulates that with meters marked for the standard frequency, a variation of 5 per cent. above or below that frequency shall not cause a change in the rate of registration in respect of such variation beyond the following limits:

	Unity power-factor.	0·5 power-factor (lag).
Commercial Grade ..	0·75 per cent.	2·0 per cent.
Precision Grade ..	0·50 ,, ,,	1·0 ,, ,,

4.7. Permissible Errors due to Change in Temperature. A change of temperature may occur in a meter due to a change in the temperature of the surrounding air, a change in the current through the main circuit, or a change in the voltage of the supply to which the voltage coil is connected. As regards the latter, the permissible error due partly or wholly to change of voltage, insofar as it affects the temperature of the meter, is included in a preceding paragraph on page 109. The permissible error due to variation in air temperature is given in Clause 39 of B.S. 37: 1937 which states that an A.C. induction meter shall not have a greater temperature coefficient than 0·1 per cent. per degree Centigrade at unity power-factor. The same limitation applies at 0·5 power-factor (lag), with marked current and at a frequency of 50 cycles per second.

The variation in the error due to heating by the main current is dealt with in Clause 41, which states that the change in the rate of registration of the meter from the time the marked current is switched on to the main circuit, to the time at which the rate of registration becomes constant at that current, shall not exceed the following values:—

	Unity power-factor.	0·5 power-factor (lag).
Commercial Grade ..	0·75 per cent.	1·5 per cent.
Precision Grade ..	0·30 ,, ,,	0·5 ,, ,,

Further, the total error in the rate of registration shall not exceed the limits allowed in Clause 37 (see Table 2 on page 108). When testing for compliance with this clause, the marked voltage shall have been continuously applied to the voltage circuit for a period of not less than six

hours immediately before the test and no current in excess of one-quarter of the marked current shall pass through the main circuit during that period.

4.8. Characteristic Curve of Single-Phase Meter. The characteristic curve of a single-phase meter is the resultant of a number of variable factors tending to cause errors in registration. The ideal meter would have a curve in which the ratio of load in watts to speed of rotor in revolutions per minute is constant at all loads. With such a meter, the curve relating load to speed of rotor would be a perfectly straight line from zero to the maximum load which the meter was capable of carrying continuously. In practice this result cannot be achieved and the aim of the designer is to eliminate the disturbing factors so far as is possible and to compensate for those which cannot be eliminated. A

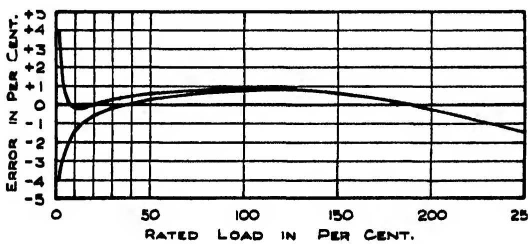


FIG. 47.—Characteristic curve for long-range single-phase meter.

characteristic curve for a typical long-range single-phase meter is shown in Fig. 47. It will be noted that over a considerable portion of this curve, i.e. between 20 per cent. or thereabouts, and 180 per cent. load, the errors are positive, and that above 180 per cent. the errors tend to become negative. The shape of the curve below 40 per cent. load is capable of some adjustment and can be made to exhibit a positive or a negative tendency as desired.

The majority of meters show these tendencies to some extent and the reasons for their presence will be considered in the following paragraphs. Apropos to the observations in Chapter I concerning the rating of meters, there does not appear to be any good reason why the point on the curve designated 200 per cent. or 250 per cent. of rated load should not be called 100 per cent. rated load, with proportionate changes to the lower values.* If this were agreed to, the only alteration necessary in the meter would be to change the rating plate. A 10-ampere

* See Appendix.

meter as at present rated would then be marked 20 amperes or 25 amperes as the case might be. It would of course be necessary to revise many clauses in B.S. 37: 1937 to line up with the new rating, but the net result would be, in the author's opinion, a more logical system of rating than that which obtains at the present time.

4.9. Factors which Influence Shape of Characteristic Curve. In order that a meter may have a straight line characteristic, the ratio of the driving torque to the braking torque must remain constant under all conditions of loading. Unfortunately this desirable condition cannot be achieved owing to the presence of several disturbing factors. The most important of these are:

1. Permeability of iron in current electromagnet varies with main current.
2. Eddy current brake acting on rotor varies with main current.
3. Friction in rotor-bearings and in register.
4. Possible lack of symmetry in electromagnet system.

Assuming that the power-factor of the load is unity, the driving torque will be proportional to the product of the two fluxes due to the voltage and current electromagnets respectively. With constant voltage and therefore constant voltage flux, the driving torque at unity power-factor will vary in porportion to the magnitude of the current flux. It will be shown later that the current flux is not strictly proportional to current but varies with the permeability of the core. With steady load conditions the braking torque is equal to the driving torque, if frictional retardation is neglected. The braking torque is the result of the rotor cutting through the magnetic fluxes set up by the permanent magnet or magnets, the voltage electromagnet, and the current electromagnet.

The main source of braking flux is of course the brake-magnet system which probably accounts for 95 per cent. of the total brake and this does not vary appreciably. The leakage flux from the voltage electromagnet also exerts a braking effect since this is cut by the revolving rotcr, but with constant voltage and frequency, the flux will also be constant and therefore will not affect the shape of the load curve. The flux from the current electromagnet varies with the main current and as this flux is cut by the revolving rotor it introduces a braking action varying with the load. The brake varies as the square of the flux (see page 115) and the variable braking action of the current electromagnet therefore constitutes the most serious of the disturbing factors. Its effect

is most noticeable above the full-load point and is responsible for the droop shown above 100 per cent. of rated load in Fig. 47. The joint action on the rotor of the voltage and current fluxes at rated voltage and current accounts for 2 to 4 per cent. of the total braking effort in the meter. The amount of braking due to each electromagnet varies according to the design. Some makers prefer to employ a relatively powerful voltage flux and a weak current flux, whereas others prefer the opposite; if a weak current flux is adopted in order to achieve a flat load curve, it may be at the expense of relatively high losses in the voltage circuit, increased errors due to varying voltage and possibly increased wear and tear on rotor pivot and jewel due to excessive vibration set up in the rotor. On the other hand a powerful current flux and a weak voltage flux may result in a meter having a drooping characteristic on overloads, but a very good performance on varying voltage and frequency, and very small watt losses in the voltage electromagnet.

The effect of friction in the rotor bearings and in the register is to cause a droop in the characteristic curve at the lower end where the load is light. Every effort should be made in manufacturing a meter to reduce friction to a minimum, by making the moving parts light in weight and by excellence of workmanship at points where friction can be created. Notwithstanding every effort in this direction, however, friction cannot be entirely eliminated and a compensating device is provided in the form of a light load adjustment, whereby a slight auxiliary torque can be created, sufficient to neutralize the braking effect of friction. By means of this adjustment the shape of the lower end of the load curve can be varied over a wide range, as shown in Fig. 47 by the branching lines, one drooping downwards and the other pointing upwards. By manipulation of the low-load adjustment the lower part of the curve can be set to occupy any intermediate position inside these lines or even to a limited extent outside the lines.

Another factor which has an influence on the shape of the load curve is the unsymmetrical disposition of the current electromagnet with reference to the voltage electromagnet: this lack of symmetry is usually unintentional and may result from carelessness in assembly of the magnetic elements. It may be due to the current electromagnet being slightly tilted, resulting in the gap in which the rotor revolves being tapered to one end or alternatively the electromagnet may be displaced to the right or left of an imaginary centre line passing through the voltage electromagnet. The effect of this lack of symmetry is to raise or lower the extremities of the characteristic curve and this may

be objectionable. As regards the light-load end of the curve, this can be rectified by means of the light-load adjustment, but the other end of the curve cannot be corrected by any simple means other than correctly positioning the current electromagnet.

4.10. Influence of Current Electromagnet on Performance. From previous observations it will be appreciated that the current electromagnet exerts a considerable influence on the performance of a single-phase meter. Briefly, it constitutes one of the principal elements in providing the driving torque and it is the main source of the variable braking flux which is responsible for the droop in the upper part of the load curve. A curve showing how the braking, due to current flux, increases with the load in a meter which has no special means of compensating for this error, is shown in Fig. 48. It will be seen that as the load increases, the error increases at a more rapid rate and is in the

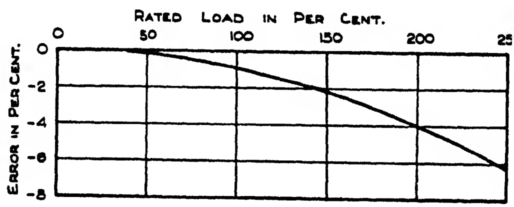


FIG. 48.—Curve showing effect of current-flux braking.

minus direction. Considering meters in the mass, it is probably correct to state that more units are registered on loads above 25 per cent. of rated load than below this figure. Any tendency for the meter to under-register on this portion of its load-curve is therefore of great importance to supply undertakings, as this means loss of revenue. It is not surprising therefore that meter engineers have devoted considerable attention to the design of the current electromagnet, more particularly with a view to improving the performance of the meter at high loads.

A number of arrangements of the current electromagnet are shown in Fig. 49. All these employ a ⊔-shaped laminated iron core of which Fig. 49 (*a*) is the simplest. The middle pole of the voltage electromagnet is also shown together with the path traversed by the current flux at the instant when there is no voltage flux. Assuming for the moment that the current flux is proportional to the exciting current, it will be noted that the flux distribution is not uniform over the whole area of the current pole faces, but is more concentrated in the region of the pole tips

adjacent to the voltage electromagnet pole. If the voltage flux is constant, the driving torque will be substantially proportional to the total current flux. The rotor-disc in revolving through this flux is subjected to a braking torque which varies as the square of the flux. Assuming that the brake at 50 per cent. load is equivalent to one unit, at 100 per

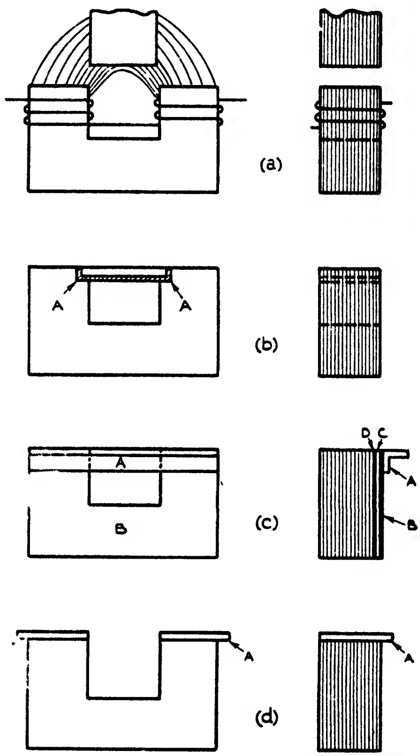


FIG. 49.—Devices to reduce effect of current-flux braking.

cent load it will be equivalent to four units and at 200 per cent. load will be sixteen units.

The braking torque varies with the flux density and although the total flux may be the same in two particular cases it does not follow that the total brake will be the same. This may be seen from a consideration of Fig. 50 which shows two poles of equal area and carrying the same total flux but having different flux distributions. The area of each

pole is divided into three equal parts and it is assumed that the flux distribution is uniform over the whole area of the right-hand pole. If the total flux per pole is represented by six units, the total flux in each area will be two units. The flux emerging from the left-hand pole is not uniformly distributed and is represented by one, two and three units respectively in the three equal areas, that is, six units total as in the right-hand pole. Since the brake is proportional to the square of the flux density, the braking effect exerted by the right-hand pole will be equal to $2^2 + 2^2 + 2^2 = 12$. The braking effect exerted by the left-hand pole will be equal to $1^2 + 2^2 + 3^2 = 14$. Thus, the left-hand pole exerts more than 16 per cent. greater brake force than the right-hand, although the total flux is the same in each case. This example emphasizes the desirability of avoiding, as far as possible, excessive concentrations of flux in the driving-magnets.

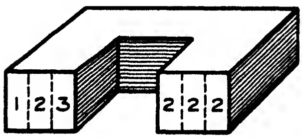


FIG. 50.—Inequalities in flux distribution over polar faces.

A slight improvement on the arrangement shown in Fig. 49 (*a*) can be effected by substituting a radius for the sharp corners of the current and voltage electromagnet pole-tips where these are adjacent. This increases the reluctance of the airgaps at these points and results in a less concentrated flux distribution. It is not possible, however, to achieve satisfactory performance on overloads with this simple form of current electromagnet, except by limiting the exciting ampere-turns to a low value, which method has disadvantages in other directions. In Fig. 49 (*b*) a construction is shown which has achieved considerable success in limiting the braking action of the current flux. As before, a ⊔-shaped electromagnet core is used and a step is formed at *A* in each of the inner pole-tips. Across the poles and resting in the steps is a strip of iron separated from the poles by a strip of non-magnetic material. Alternatively a slot in the side of each pole instead of a step, may be used, with the strip of iron wedged in the slots but separated from the poles as before with non-magnetic material. The strip functions as a magnetic shunt and carries a proportion of the current flux, thus diverting it from the rotor. From the smallest load up to the point where the shunt becomes saturated, a proportion only of the total current flux cuts through the rotor to produce driving torque. Above the saturation point, the whole of the additional flux set up by the additional current cuts through the rotor and thus the rate of increase

of torque with respect to rate of increase of current is greater than it was below the saturation point. By suitably proportioning the shunt, the additional driving torque necessary to overcome the additional current electromagnet braking can be provided. In this manner a reasonably flat load curve can be ensured up to 200 per cent. or more, of rated load.

A current electromagnet having a saturable magnetic shunt arranged in a different manner is shown in Fig. 49 (*c*). Here, the magnetic shunt is an inverted L sectioned iron member bridging the poles and extending the full width of the electromagnet. The shunt *A* is spaced from the outer core stamping *B* by a thin brass separator *C* and the outer core stamping is also separated from the rest of the core by a thin brass lamination *D*. The operation of the shunt is very similar to that described in the previous example. Another method of reducing current electromagnet braking is shown in Fig. 49 (*d*); here the pole-faces of the electromagnet are covered by iron plates which are larger in area than the poles and project beyond the faces of the latter on two sides. The effect of this is to reduce the flux density at the pole face, and since the braking with a given flux is proportional to the square of the flux density, the result is a reduction in the braking action. A number of methods of improving performance on heavy loads have been adopted by different manufacturers and all utilize the principle of the magnetic shunt or the dispersion of the flux over a larger area in order to reduce the flux density.

The error in the load-curve due to varying permeability of the iron in the current electromagnet, is manifested more particularly at low loads. This effect is shown by means of the curve in Fig. 51. The magnitude of the error varies in different types of meter and depends upon the relative proportions of the iron and air paths in the magnetic circuit. A meter having a short path in air for the current electromagnet flux and a relatively long path in the iron core, might be expected to show this characteristic in a more marked manner than a meter having a relatively long airpath for the current flux. Various methods have been adopted to reduce this error, one of which is to introduce into the current electromagnet core a proportion of laminations punched out of electrolytic iron or one of the high permeability nickel-iron alloy steels such as Mumetal, Permalloy or the like. All these metals have a very high permeability at low inductions where the permeability of the more usual dynamo iron is very low. The effect of introducing a few laminations of these special metals is to increase the

current flux over the range where the flux is below normal and thus to make the meter faster over this range.

An alternative method is to introduce a constriction in part of the magnetic circuit traversed by the current flux, thus increasing the flux density at the constriction. This causes part of the iron to operate at a higher point on the permeability curve for a given load and results in

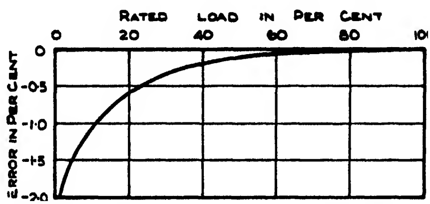


FIG. 51.—Errors due to varying permeability of current-electromagnet core.

the curve shown in Fig. 51 rising more steeply. Two variations of this method are shown in Fig. 52 (*a*) and (*b*). The first shows an airgap *A* separating the two halves of the electromagnet core. A strip of non-magnetic material *B* extends over the lower edges of the core stampings

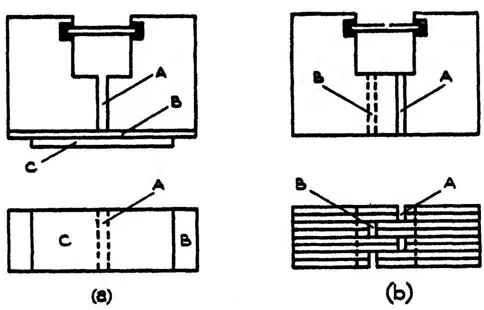


FIG. 52.—Current electromagnets with restricted sections.

and separates the core from a strip of iron *C*, which acts as a magnetic shunt to the airgap *A*. For small values of the current in the main circuit, the greater part of the current flux will be carried by the iron strip *C*, which will operate at a relatively high flux density compared with the density in the main portion of the electromagnet. By the time the strip *C* is saturated, a large part of the total flux will be crossing the gap *A* and the core will be operating at a flux density sufficiently

high to minimize the errors due to low permeability. In the method shown in Fig. 52 (*b*), the current electromagnet is built up with pairs of L-shaped stampings, one of the pair having a shorter base than the other. They are assembled in groups of four or more stampings, leaving a gap between opposing ends as at *A*. The next group of four or more are turned over so that the gap occupies a position as at *B*; the groups alternate in this manner until the core is complete. By assembling thus, the flux at low loads is caused to follow a devious path through the stampings at the base of the core and the flux density is much higher than in the vertical limbs. After saturation of this part the side limbs will operate at a flux density sufficiently high to avoid serious errors due to low permeability.

4.11. Influence of Voltage Electromagnet on Performance. Unlike the current electromagnet to which reference has already been made, the voltage electromagnet is not normally subjected to wide variations in flux density, although different parts of the magnetic circuit may be working at different densities. The conventional form of voltage electromagnet has been shown in Figs. 14 and 43 on pages 48 and 100. It has been explained that leakage flux only, and not main flux, cuts through the rotor and reacts with the current flux to produce the driving torque. This leakage flux also exerts a braking action on the rotor, the effect of which varies as the square of the flux and since the latter is proportional to the voltage of the supply, the braking is proportional to the square of the voltage. Under normal conditions variations in voltage are small* and errors arising from this cause are not important. Some Area Boards however, distributing over a large area, may have different declared voltages in different parts of the area. In such cases it is customary to purchase meters marked with a range of voltage such as 200–250 volts, and to test these at some intermediate voltage such as 230 volts. Provided that the voltage variation error for the type of meter employed is small, this practice is convenient, as it permits a meter to be taken from store and used at any voltage within the marked range. As might be expected, the effect of an increase in voltage is to increase the voltage braking, with the result that the meter may register slower at the higher voltage with constant watts.

With a view to keeping the error due to change in voltage at a low

* At the time of writing, conditions are abnormal owing to acute shortage of generating plant, and reduction of voltage at times of peak load occurs during the winter season. It is to be anticipated that this undesirable state of affairs will be overcome within the next few years.

value, it is usual to work the iron in the voltage electromagnet at a low flux density, so that the braking action of the voltage flux shall be small relative to the total braking flux acting on the rotor. There is a limit to this procedure however, since the torque of the meter is proportional to the product of the voltage and current fluxes. If the voltage flux is reduced the current flux must be increased in order to produce a given torque and the result of this is to increase the braking due to current flux with consequent poor performance on current overload. Some manufacturers have endeavoured to overcome this difficulty by so proportioning the various parts of the voltage electromagnet that with increase in applied voltage, the leakage flux increases at a rate greater than the rate of increase in the voltage which produces it. In this way the driving torque increases at a greater rate than the increase in voltage and by an amount sufficient to compensate for the increased voltage braking.

The method whereby this is accomplished will be understood by reference to Fig. 43 on page 100. The middle limb of the voltage electromagnet carries the total voltage flux which divides between the two outer limbs in substantially equal parts. Part of the flux in the outer limbs returns to the centre limb through the inwardly projecting poles and the remainder in the form of leakage flux returns through the rotor-disc. It is this latter flux which is productive of driving torque and by causing it to increase at a rate greater than the rate of increase of voltage, the torque can be augmented. The voltage electromagnet core is constructed with laminations of silicon steel, the permeability of which varies with the flux density. Starting with a low density the permeability is low, but rises with the density until an induction of approximately 6,000 lines per square centimetre is reached; at this point the permeability is a maximum and any further increase in flux density results in a reduction in permeability. The section of the iron in the electromagnet is proportioned so that at normal working voltage the middle limb is operating with a flux density substantially below 6,000 lines per square centimetre and the inwardly-projecting poles substantially above this value. It follows from this that the reluctance of the magnetic path through the inwardly-projecting poles increases with increase of voltage and consequently a proportionately greater driving flux will result therefrom.

4.12. Factors which Influence Frequency Errors. Many factors contribute to the error resulting from change in frequency. The effect of each is small in itself and some tend to cancel out the effect of others.

The voltage flux varies inversely with the frequency but the current flux is not affected. The permeability of the voltage electromagnet core will be changed and different parts of the magnetic circuit may be changed by different amounts. The copper loss and the iron loss in the voltage electromagnet vary with the frequency and similarly the phase displacement between applied voltage and leakage flux. The impedance of the paths traversed by the eddy currents in the rotor disc changes and the thickness of the disc itself has an influence on the results obtained. To attempt to assess the relative importance of these varying factors is a complex matter and a general statement as to the probable effect of a change in frequency will be of more practical value. In the majority of cases, with a load having unity power-factor, the effect of an increase in frequency is to make the meter slower and a

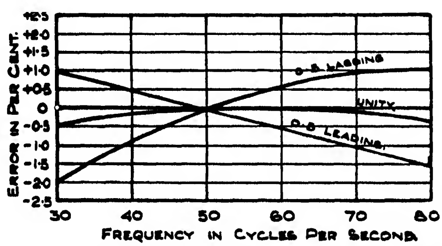


FIG. 53.—Effect of varying frequency on the error of a 50 c/s meter.

reduction in frequency to make the meter faster. With a load having 0·5 power-factor (lagging), the effect of increase in frequency is to make the meter faster and a reduction in frequency to make the meter slower. This statement must not be regarded as an invariable rule however, as the author is aware from examination of a large number of tests on different makes of meter that the effect of a change of frequency on a few meters is exactly opposite from the above. Further, in two instances where precision grade meters made by different manufacturers were checked by the N.P.L. an increase in frequency caused the meters to run slower on non-inductive and inductive loads and a reduction in frequency caused them to run faster under the same conditions. From the foregoing it will be appreciated that no rule can be laid down as to how meters in general will behave with change of frequency, although all meters of the same type may be expected to behave in the same manner. In Fig. 53 is reproduced a curve showing

the effect of frequency change on a 50 c/s induction meter. It would not be correct to describe this as a typical performance since all meters do not behave in the same manner, but many meters, probably the majority, may be expected to follow on the general lines of this curve.

4.13. Factors which Influence Temperature Errors. The error of a meter resulting from a change in temperature may be due to a change in the ambient temperature or a change in the load conditions causing heating in the voltage or current electromagnet. The temperature inside the meter case will normally be higher than the external temperature owing to the energy losses in the windings. A number of factors contribute to the temperature error of a meter, some tending to make the meter fast and others to make it slow. In a meter not fitted with temperature compensation, an increase in the temperature of the air inside the meter case will have the following results:—

1. The resistance of the voltage coil will increase. This change will have little effect on non-inductive loads but the phase-angle of the voltage flux will be reduced and this will cause the meter to register slower on inductive loads. The effect increases as the power-factor of the load becomes lower
2. The resistance of the quad band will increase. This will reduce the phase compensation applied to the voltage flux and will cause the meter to register slower on inductive loads, but will have no effect on non-inductive loads.
3. The resistance of the low-load adjustment plate or loop, if fitted, will be increased and consequently the friction compensation will be reduced. This will cause the meter to register slightly less on low loads. In addition, since the induced current in this plate is complementary in its effect to the induced current in the quad band, the meter will register slightly less on inductive loads.
4. The resistance of the rotor disc will increase. This will reduce the eddy currents induced in the disc and will also reduce the driving torque under all conditions of load. On the other hand, the braking torque will be reduced in the same proportion with the result that the two effects will tend to cancel out.
5. The flux in the gap of the brake magnet or magnets will decrease with the result that the braking torque will be reduced and the meter will register faster under all conditions of load. This effect will vary according to the composition of the magnet steel,

chrome and tungsten steels being affected to a greater extent than cobalt and nickel-aluminium steels.

In addition to the foregoing, a change in temperature may result in distortion or alteration in the relative spacing of various parts. The effect of this cannot be predicted as it will vary with every different design of meter. Generally speaking, however, this effect is small and usually can be neglected for the range of temperature covered by normal working conditions.

The overall effect of these various factors in an uncompensated meter is that an increase in temperature results in the meter registering faster on non-inductive loads. The reason for this is, that the reduction in braking torque is greater than the reduction in driving torque. On

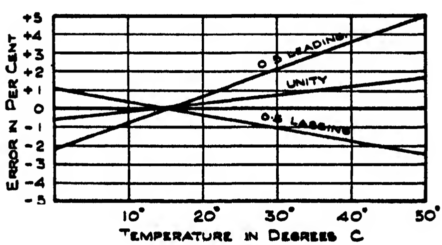


FIG. 54.—Effect of varying temperature on the error of a 50 c/s meter.

inductive loads the tendency is for the meter to register slow, relative to the non-inductive load registration; the difference increases with reduction in power-factor and there will be some particular value of power-factor at which the meter will be correct at all temperatures. In Fig. 54 is a curve showing the performance of an induction meter at 50 per cent. load over a wide range of temperature. It will be noted that the change in the error is linear and that with increase in temperature this meter registers faster at unity power-factor and slower at 0·5 power-factor (lag.). At some intermediate point around 0·7 power-factor this meter would be approximately correct at all temperatures.

The methods adopted to compensate for temperature errors have varied considerably in the past, but the majority of modern meters which are compensated, make use of a device which has the effect of minimizing the loss of brake force exerted by the brake-magnet system as the temperature rises. In some cases where two brake magnets are

used, a proportion of the flux from the magnets is shunted through a block of magnetic material, the permeability of which drops considerably with increase of temperature. At low temperatures a proportion of the flux is carried by this magnetic shunt but as the temperature rises and the meter tends to run faster, this tendency is opposed by a reduction in the flux passing through the shunt and an increase in the flux cutting through the rotor disc. By correctly proportioning the magnetic shunt the temperature error of the meter may be reduced to negligible proportions over a wide range of temperatures.

Another method which is adopted when one brake magnet only is employed is to fit a thin plate of magnetic material on to one of the brake-magnet poles in such a manner that the braking flux is distributed over a comparatively large area. The permeability of this pole-plate is reduced with increase in temperature, with the result that the brake flux becomes more concentrated in the area of the magnet pole and the braking effect tends to increase. If the temperature is raised sufficiently, the pole-plate will become non-magnetic, beyond which point the compensating device will cease to function. This applies equally to the magnetic shunt referred to in the previous paragraph, but in practice, the temperature at which the device becomes ineffective is well outside the range within which the meter is likely to operate.

It will be noted that the foregoing methods of applying compensation for temperature errors result in a reduction in the rate of registration as the temperature rises, relative to the registration of an uncompensated meter. This reduction in the rate is effective at all loads and at all power-factors. At some critical power-factor, each type of meter, when uncompensated for temperature, will have zero temperature error and the effect of applying temperature compensation will be to increase the temperature error in the negative direction on inductive loads at power-factors below the critical value. In practice, this is not found to be serious and in many cases the temperature error at 0·5 power-factor is less than the corresponding error at unity power-factor.

4.14. Torque of Single-Phase Meter. The torque or driving force exerted by the rotor of a single-phase meter is the result of a number of factors each of which can be varied when designing the meter. The design is a compromise between a number of these variables and while generally speaking, a high torque is regarded as desirable, it must be considered in relation to the means whereby it is achieved. The main factors which determine the torque of the meter are:

1. The magnitude of the leakage flux set up by the voltage electromagnet.
2. The magnitude of the current flux set up by the current electromagnet, and
3. The thickness and resistivity of the rotor disc and the effective radius at which the above-mentioned fluxes operate.

The necessary phase relationship between these fluxes, in order to ensure accuracy of registration at all power-factors, was explained in page 56.

The torque necessary to ensure reasonable accuracy over a wide range of measurement and maintenance of the initial accuracy over a long period of time, depends upon the frictional resistance to be overcome by the rotor. This resistance consists of friction in the rotor bearings and in the register, and as the friction is liable to increase with time, the ultimate friction after a period of years in service must be taken into consideration. Apart from the absolute value of the friction, the variation in friction is an important factor and in order that this latter may be relatively unimportant, the work done by the rotor in overcoming friction must be small by comparison with the work done in overcoming magnetic braking. In B.S. 37: 1937, a recommendation is made in Appendix A that the full-load torque of a meter should be not less than three centimetre-grams. This is to ensure that the effect of register friction shall be small and that initial accuracy shall be maintained for a reasonable period. Most single-phase meters made in this country have a torque higher than this value and many have a torque of 4 to 5 centimetre-grams. That this is not the only criterion however, may be judged from the fact that many D.C. commutator ampere-hour meters have a torque in the region of 12 centimetre-grams and yet cannot conform to requirements, while D.C. mercury motor ampere-hour meters, which in some ratings have a torque less than 3 centimetre-grams can put up a good performance.

The torque of a single-phase meter can be increased by an increase in the voltage flux which cuts through the rotor disc. To do this, the energy loss in the voltage coil must be increased and as this loss is continuous for twenty-four hours per day throughout the life of the meter it is not regarded favourably by some purchasers. Furthermore, increased voltage flux means increased error due to change in voltage, which is undesirable if carried beyond certain limits. An increase in the current flux also results in an increase in torque, and since this requires extra ampere-turns on the current electromagnet, the losses in

this circuit are increased. This is not a serious matter in itself, except insofar as it sets up additional heating which is undesirable at high loads. The most objectionable feature is the disturbing effect of current braking which causes the curve to droop on overloads. The torque can also be increased by increasing the thickness or the conductivity of the rotor disc. This latter is always made from aluminium for the sake of lightness. A copper disc of the same thickness will give a higher torque in the ratio of the relative conductivities of copper and aluminium, but the weight of copper is greater than aluminium and on a torque/weight ratio, copper is inferior.

For a given material the torque will be proportional to the thickness of the disc, and the weight of the rotor will go up in nearly the same proportion. The clearance in the gaps between the disc and the pole faces of the driving and braking magnets will be reduced if a thicker disc is used thus increasing the risk of stoppage of the meter due to the presence of small particles of foreign matter in the gap. Finally, the torque can be increased by increasing the diameter of the rotor disc and increasing the effective radius at which the driving electromagnets are operating. The increase in torque will be in proportion to the increase in the effective radius, but this involves a heavier rotor and possibly a larger meter, both of which may be objectionable; thus it will be seen that the torque of a meter is determined by a number of factors, each of which may involve the incorporation of some undesirable feature and a compromise must be arrived at for any design, in which due weight is given to the results desired and the sacrifices to be made for their achievement.

4.15. Comparative Performances of Single-Phase Meters. It has been a common practice amongst purchasers of electricity meters, when calling for tenders for annual contracts and the like, to demand from the manufacturers certain technical information. This information has been incorporated in a formula whereby the purchaser endeavours to appraise the qualities of various makes of meter relative one to another. In its most elementary form, the ratio of torque in millimetre-grams to weight of rotor in grams has been taken as the criterion and the meter showing the highest ratio has been judged to be superior. The full-load speed of the rotor in revolutions per minute is an important factor, since the higher the speed, the greater will be the wear on pivot and jewel in a given time. Accordingly, the next step was to incorporate this factor in the formula and call the result the "permanence factor". The formula has now become:

$$\frac{\text{Torque in millimetre-grams} \times 100}{\text{Weight of rotor in grams} \times \text{R.P.M. at full load}}$$

$$= \text{Permanence Factor.}$$

But a meter which achieves a high torque by means of a relatively great expenditure of energy in the voltage circuit would obtain undue credit from the application of this formula, so the next step is to incorporate the watt-loss in the voltage circuit and call the result the "efficiency factor". The formula now becomes:

$$\frac{\text{Torque in millimetre-grams} \times 100}{\text{Weight of rotor in grams} \times \text{R.P.M. at full load} \times \text{Watts in voltage coil}}$$

$$= \text{Efficiency Factor.}$$

The efficiency factor of a meter can be raised by reducing the loss in the voltage coil and increasing the loss in the current coil, but the result would probably be an inferior meter from the point of view of performance. It could also be improved by reducing the clearance between the rotor disc and the pole faces of the electromagnets thus increasing the torque but increasing also the risk of stoppage due to foreign matter falling on the surface of the disc. The formula completely ignores the friction load imposed by the register and the rotor bearings, which should have a low value, and which depends upon the quality of the workmanship incorporated in them. It also ignores the wearing qualities of the bottom pivot and jewel, factors more important perhaps than any incorporated in the formula. The wearing qualities of the pivot depend upon the kind of steel from which it is made, its hardness, degree of polish, and the dimensions of its hemispherical face. The wearing qualities of the jewel are related to the hardness of the material used, (sapphire or diamond), the freedom from inclusions, the degree of polish in the cupped surface, and the radius of the cup relative to the radius of the pivot. In the opinion of some authorities the orientation of the crystal structure of the jewel is also important.

Apart from the above, the wear on both pivot and jewel depends upon whether they run dry or lubricated, whether the lubricant is suitable or not, and lastly but by no means least, on the nature and the magnitude of the parasitic forces acting on the rotor, which expend themselves on the surfaces in contact. It will be seen from the foregoing that a formula can only serve as a criterion, other things being equal. The writer ventures to assert that no formula can give a reliable comparison

between different makes of meter because, included in "other things being equal" are unknown factors which cannot be assessed by the purchaser and which are of at least equal importance to the life and performance of a meter as are the factors included in the formula.

4.16. Technical Data Concerning Single-Phase Meters. In Table 3 are given Technical Data relating to a number of single-phase meters manufactured in this country. The figures are the results of actual tests on sample meters and do not necessarily agree exactly with information given in the makers' catalogues. All meters are rated at 10 amperes, 230 volts, 50 c/s, and all are classed as "long range". The torque and speed were measured with a load of 2·3 kW, i.e. normal full load, and the shunt loss was taken at 230 volts, 50 c/s. Register friction was determined by observing the change in the error of the meter when the register was removed, and in each case the figure stated in the table is the average of six consecutive readings. In view of the comments concerning "Permanence Factor" and "Efficiency Factor" in Section 4.15

TABLE 3

Technical Data: Single-Phase Meters: 10 A, 230 V, 50 c/s

Maker	Torque in cm-g	Shunt loss in watts	Rotor weight in grams	Speed in R.P.M. at F.L.	Register friction at	
					$\frac{1}{20}$ load	$\frac{1}{40}$ load
					%	%
A	2·9	1·50	18·7	34·5	1·7	2·0
B	2·9	1·25	19·6	23·0	2·3	3·6
C	3·1	1·15	21·7	30·7	2·1	3·4
D	3·3	1·10	16·7	28·7	1·3	1·5
E	3·3	1·20	18·5	18·2	2·5	3·0
F	3·6	1·65	13·3	34·5	0·7	1·0
G	3·6	1·25	23·7	23·0	1·0	1·2
H	3·8	0·90	22·3	23·0	1·3	1·7
J	4·4	1·00	23·2	23·0	0·8	0·8
K	4·6	1·05	17·1	23·0	0·9	1·4
L	4·8	1·00	23·3	23·0	1·7	2·5
M	5·2	1·65	16·2	28·7	0·8	0·9
N	6·6	1·10	19·5	17·25	—	—

and the desire to avoid the possibility of misleading comparisons being made, the names of the manufacturers are omitted. While the figures convey a fairly accurate picture of comparative performances, it must be recognized that a test on a single specimen may not represent the average performance for its type and may in fact be better or worse than the average. Further it should be noted that as regards register friction, the 10-ampere rating represents the worst case and 5-ampere or 25-ampere ratings may be expected to give better results.

4.17. Influence of Transformer Errors on Performance. The errors of current and voltage transformers are considered in Chapters XII and XIII, and are of two kinds, namely errors in ratio and errors of phase displacement. It is standard practice to wind current transformers so that with rated current through the primary winding, the current delivered to the burden by the secondary winding is nominally 5 amperes. In the case of voltage transformers, with rated voltage applied to the primary winding the voltage across the burden connected to the secondary is nominally 110 volts. A single-phase meter for use with a current transformer will have a current coil wound for a rated current of 5 amperes and if a voltage transformer is used in addition, the voltage coil of the meter will be wound for a rated voltage of 110 volts.

When a current transformer is connected to a single-phase meter the errors of the transformer are added to the errors of the meter. Thus, if a transformer having a ratio error of + 1·0 per cent. at rated primary current is connected to a single-phase meter having an error of + 1·0 per cent. at rated full load, the error of the combination will be + 2·0 per cent. On the other hand, if the error of the meter is —1·0 per cent., the error of the combination will be zero as the two errors will cancel out. It is a common practice to calibrate the meter in conjunction with its current transformer, as in this way the errors of the transformer which cannot be adjusted can be offset by introducing an equal error of opposite sign into the meter curve. This practice which usually is desirable is not always convenient and if the transformer errors have been previously determined, the necessary corrections can be applied to the meter when calibrating the same without transformer.

The shape of the meter curve from 20 per cent. of rated current upwards cannot be altered to any appreciable extent and consequently the adjustment to compensate for transformer ratio errors can only be made at one load. If the ratio errors vary considerably with variation in primary current, an average error must be taken and the meter

curve raised or lowered by an amount which will give the best overall performance. A transformer having a considerable error which is constant at all loads would present no difficulty in use since any reasonable value of absolute error can be eliminated in calibrating the meter; a difficulty which cannot be overcome is the variation in the ratio error at different loads. It is for this reason that in addition to specifying the absolute values of the permissible ratio error in a transformer, the permissible variation in the error is also specified in the case of metering transformers. Details of these permissible errors and variations are given in the section dealing with current transformers on page 423.

The ratio errors of a current transformer tend to increase rapidly below 20 per cent. of rated current and in the British Standard for Instrument Transformers, B.S. 81: 1936, no limits are imposed on errors arising below 10 per cent. of rated current. It is possible to apply some correction to the meter curve at low loads by the use of the low-load adjustment, but the use of this device is limited. Any attempt to correct for excessive low-load errors in transformer ratio leads to trouble in other directions and in particular to a tendency on the part of the meter to register when there is no current passing in the main circuit.

The influence of a current transformer ratio error on the performance of a meter is the same whatever the power-factor of the load may be, that is, a ratio error of + 1·0 per cent. will affect the meter by this amount at any power-factor. A phase-displacement error in the current transformer will have a negligible effect on the meter when the power-factor of the load is unity, but the effect will increase as the power-factor becomes lower and will reach a maximum when the power-factor is in the region of zero. In Table 4, the effect of phase-displacement errors of various magnitudes on the performance of a meter at various power-factors is shown.

It will be observed that for any particular error of phase displacement in the transformer, the percentage error in the meter registration, starting at unity power-factor, increases comparatively slowly at first with reduction in power-factor, but increases rapidly after the power-factor of the load falls below 0·5. It is convenient to memorize the fact that a phase-displacement error of 1 deg. or 60 min. will cause a change in the meter error at 0·5 power-factor of 3·0 per cent. and that larger or smaller phase displacements will cause proportionately larger or smaller errors at the same power-factor.

The reversed secondary current of a current transformer usually

TABLE 4

Errors in per cent. introduced into Meter Readings due to Phase-Displacement Errors in Instrument Transformers.

Phase Angle in Minutes	Power-Factor of Load									
	1·0	0·9	0·8	0·7	0·6	0·5	0·4	0·3	0·2	0·1
10	0·0	0·1	0·2	0·3	0·4	0·5	0·7	0·9	1·4	2·9
20	0·0	0·3	0·4	0·6	0·8	1·0	1·3	1·8	2·8	5·8
30	0·0	0·4	0·6	0·9	1·1	1·5	2·0	2·8	4·3	8·7
40	0·0	0·5	0·9	1·2	1·5	2·0	2·7	3·7	5·7	11·6
50	0·0	0·7	1·1	1·5	1·9	2·5	3·3	4·6	7·1	14·5
60	0·0	0·8	1·3	1·8	2·3	3·0	4·0	5·6	8·5	17·4
70	0·0	1·0	1·5	2·1	2·7	3·5	4·7	6·4	9·9	20·2
80	0·0	1·1	1·7	2·3	3·1	4·0	5·3	7·4	11·4	23·1
90	0·0	1·2	1·9	2·6	3·5	4·5	6·0	8·3	12·8	26·0
100	0·0	1·4	2·1	2·9	3·8	5·0	6·7	9·2	14·2	28·9

leads the primary current by a small angle of phase displacement and examples of this will be found in Section 12.15. The effect on the meter of this leading current is to increase the phase displacement between the voltage and current fluxes and consequently the meter will register more than the correct amount. Correction for this error is made by means of the inductive-load adjusting device, which is required to reduce the phase displacement between voltage and current fluxes by an amount equal to the phase-displacement error of the current transformer. As in the case of the ratio error, the compensation for phase error can only be made for one absolute value of phase displacement and if the phase error varies at different loads a correction must be made which gives the best overall result. For this reason a limit is imposed, in current transformers for use with meters, on the permissible variation in the phase-displacement error, in addition to a limitation in its absolute value.

A high-voltage single-phase meter requires the use of a voltage and a current transformer and as it may be inconvenient to carry out the calibration tests on a high voltage circuit, it is usual to determine the

voltage transformer errors separately and to make the necessary corrections to the meter on a low-voltage circuit. Since the burden on a voltage-transformer is usually known and is not subject to variation under working conditions, the error can be determined at the working burden and the necessary corrections to the meter can be made with a reasonable degree of accuracy. A ratio error of 1·0 per cent. plus will cause the meter to register fast by the same amount, as in the case of a current transformer. The phase-displacement error of a voltage transformer will have exactly the opposite effect on the meter from the phase-displacement error of a current transformer if in both cases the phase-angle is leading as is probable. The reason for this is that normally the voltage flux in a meter lags approximately 90 deg. behind the current flux (at unity power-factor), and whereas a leading current from the current transformer will increase the phase displacement between the fluxes, a leading voltage from the voltage transformer will reduce the phase displacement.

CHAPTER V

PREPAYMENT METERS: GENERAL PRINCIPLES

5.1. Development of Prepayment Meters. A prepayment meter is an instrument comprising the combination of a direct-current or an alternating-current electricity meter element with a coin-freed mechanism, which latter is wholly or partially controlled by the meter element to which it is attached. A switch incorporated in the coin-freed mechanism opens the main circuit and cuts off the supply to the consumer when the value of the energy or other commodity corresponding to the coin or coins inserted has been used.

Prepayment meters have been used more extensively in Britain than in any other country, and have played no small part in making available at a moderate cost, a supply of electricity to the small consumer. A variety of tariffs have been introduced, largely with the object of encouraging the use of electricity and electrical appliances amongst domestic consumers, and as a result, a great variety of prepayment meters have been developed.

A quarter of a century or more ago, the prepayment meter was a comparatively simple mechanism, and moderate in first cost. With increasing popularity and the introduction of special tariffs, manufacturers developed and incorporated in prepayment meters many new devices. The necessity for some of these devices was doubtful, the multi-coin prepayment meter being a case in point, but a fashion having been started, every manufacturer was compelled by stress of competition to follow the lead. As a result of a decade of intensive development work in the years immediately preceding the second World War, prepayment meters became exceedingly complicated and in many cases costly to manufacture. The outbreak of war put a stop to further development, and subsequent experience has proved that excessive complication is unprofitable to the supply authority because of the high cost of maintenance. It is probable that the trend in the future will be a return to simplicity and to the exclusion of many of the non-essential devices now in use, in order to avoid these unnecessary costs.

5.2. Advantages and Disadvantages of Prepayment Meters. The use of prepayment meters is confined almost entirely to domestic consumers

taking a two-wire supply from direct-current or single-phase alternating-current mains.

Polyphase prepayment meters have been made for special purposes, but very few are in use. The prepayment consumer pays for energy by instalments and cannot get into debt: this is a great convenience to the small wage earner who may experience difficulty in meeting a quarterly account for which no provision has been made. Many consumers prefer to know how much is being expended on electricity week by week and can take steps to economise should this be necessary. The improvident are compelled to pay for energy before it is used.

Apart from payment for energy supplied, the prepayment meter may also be used to collect hire charges or hire-purchase instalments on installations and apparatus. Thus, the cost of wiring consumers' premises can be recovered by instalments and the hire charges for an electric cooker, or the hire-purchase instalments on electric fires, kettles, or the like, can be collected. Because of the facility thus offered, the consumer is able to purchase and use electrical appliances which otherwise might be beyond his capacity to pay for in a lump sum.

The disadvantages of the prepayment meter from the point of view of the consumer are, that the price of energy is slightly higher than when supplied through a credit meter, and the supply is liable to interruption, possibly at an inconvenient moment, if the consumer neglects to maintain a credit reserve in the meter. As regards the higher price of energy, this is necessary in order to recover the additional cost of the prepayment meter above that of a corresponding credit meter and also because the cost of maintenance is higher. The opening of the switch and the interruption of the supply can be avoided if the consumer will observe, from time to time, the state of the credit indicator and will insert another coin before credit is exhausted. This disadvantage is much less pronounced where the operative coin is one shilling than where it is one penny, as obviously the switch may open twelve times as frequently due to credit exhaustion in the latter case.

From the point of view of the supply authority, the advantages of the prepayment meter are that there are no bad debts and no accounts to render. The sale of energy is increased, partly because the consumer knows in advance how much he is paying, and partly because he is encouraged to make more extensive use of electrical appliances owing to the facility for payment by instalments. Consumers supplied through a credit meter who habitually fail to pay their accounts promptly, can be effectively dealt with by installing a prepayment meter. In addition,

if they have incurred a debt which they refuse or are unable to pay off, this can be recovered through a prepayment meter, set to collect a higher price per kWh until such time as the debt is completely paid off. In districts where the occupants of tenements or flats frequently change their residence without giving notice to the supply authority, the installation of prepayment meters ensures that such tenants cannot leave without paying for the energy they have consumed. The disadvantages of the prepayment meter on the other hand, are higher first cost and increased maintenance charges. However, since these are recovered from the consumer, by charging a higher price per kWh, the disadvantages are not serious.

5.3. Early Types of Prepayment Meter. Some of the early types of prepayment meter were very primitive by comparison with their modern counterparts. They were easily defrauded and did not incorporate what to-day would be considered as bare essentials. They were introduced during the period when direct-current distribution was the more usual system, and it is not surprising therefore, that electrolytic types received first consideration. Brief reference may be made to two types of electrolytic prepayment meter which were used in this country, namely, the Long-Schattner and the Mordey-Fricker.

The Long-Schattner Electrolytic Prepayment Meter comprised a pivoted beam carrying near one end a bucket for the reception of prepaid coins, and also the suspended copper anode of an electrolytic cell. The cathode of the cell was a copper vessel containing the electrolyte. At the extremity of the beam a copper stirrup was fitted, the forks of which dipped into two cups containing mercury. The stirrup and mercury cups constituted a switch in the consumer's main circuit, and when a coin was inserted in the meter, it fell into the bucket, the additional weight of which caused the beam to tilt and the switch to close. This enabled the consumer to draw current from the supply via the electrolytic cell, and in so doing, copper went into solution at the suspended anode and was deposited on the walls of the cell in an amount proportional to the value of current consumed in the period.

In this process the anode became lighter until finally the beam tilted and the stirrup was lifted out of the mercury cups, thus opening the main circuit. The insertion of an additional coin or coins restored the supply and the process was repeated. Where the meter was installed, it became necessary from time to time to renew the electrolytic cell, a messy and lengthy operation to carry out on consumer's premises. The collection of prepaid coins necessitated the removal of the meter cover

to obtain access to the bucket in which they were stored, after which the beam had to be balanced by means of a sliding counterpoise. It is not surprising that this device was superseded by more convenient means when they became available.

The Mordey-Fricker Electrolytic Prepayment Meter is another example of an early construction. It consisted of a glass vessel containing a copper nitrate solution in which was suspended a copper cathode. The anode consisted of a roll of perforated copper foil which could be unwound by means of a sprocket engaging with the perforations. A clutch member, consisting of two portions, one of which was secured to the sprocket and the other to a handle projecting outside the meter cover, could be caused to engage when a coin was inserted through a slot in the cover. Normally the two halves of the clutch were free, but on inserting a coin and turning the handle, a definite length of copper foil could be unwound off the roll into the electrolyte and the coin would then fall into the cash receptacle. Immersion of the foil in the electrolyte completed the consumer's main circuit, and as current passed through the electrolytic cell, copper was transferred from the anode to the cathode. The amount of copper transferred in this manner was proportional to the consumption in ampere-hours, and when the whole of the foil immersed in the electrolyte had been transferred to the cathode, the consumer's main circuit was interrupted. In this meter, as in the Long-Schattner meter, it was necessary from time to time to renew the anode and to replace the cathode and the electrolytic cell.

Following the electrolytic types the disadvantages and inconveniences of which are obvious, motor meters were brought into use and prepayment mechanisms were developed for incorporation with these. An early example was introduced by Hookham which was a considerable advance on what had been available hitherto. Attached to the top of the meter case was a cylinder containing several hundred phosphor-bronze balls about $\frac{5}{16}$-in. diameter, arranged in a spiral groove in the cylinder. The lower extremity of the groove terminated immediately above a channel secured to a pivoted beam, carrying at one end, the prongs of a mercury switch. The insertion of a coin into the mechanism, and the manipulation of a lever projecting through the cover of the meter, released a ball from the magazine and allowed it to fall into the channel. The weight of the ball caused the pivoted beam to tilt, thus closing the mercury switch and completing the main circuit to the consumer; the ball then rolled to the lower extremity of the channel, at which point its further movement was arrested by an

escapement device. Twelve balls could be accommodated in the channel at one time.

A crank mounted behind the meter register was joined by a connecting rod to the escapement device, and as current was consumed, the crank caused the escapement to rock back and forth. Each reciprocation of the escapement released one ball from the channel into a reservoir, and when the last ball had been released, the beam would tilt in the opposite direction, thus opening the switch in the consumer's circuit. The gearing of the register was so arranged that consumption of current in a given time, equivalent in value to one coin, would result in one revolution of the crank and the release of one ball from the channel. When the meter reader called periodically to collect the money from the meter, he would at the same time remove the balls from the reservoir, and transfer them to the magazine for re-use.

Following the Hookham Prepayment Meter, an endeavour was made by Sprague (Chamberlain and Hookham) to simplify construction and to reduce initial cost. Sprague's prepayment mechanism had few working parts and was very compact. The essential parts comprised two wheels mounted on an arbor, each having ten prominent teeth. A spring tended to hold the wheels in a zero position against a stop. A cylinder arranged to receive a coin was mounted adjacent to one of the wheels and on inserting a coin and rotating the cylinder the coin would engage one of the wheel teeth and advance the wheel one-tenth of a revolution. The coin would then fall into a coin receptacle. The spring tended to return the wheels to their initial position but was prevented from so doing by a pallet, acting as a pawl, which engaged a tooth of the second wheel.

A copper stirrup bridging two cups containing mercury was mounted on one end of a pivoted lever, and acted as a switch in the main circuit. The other end of the lever projected into the path of a pin on one of the wheels and when the latter were in the zero position the pin lifted the stirrup out of the mercury cups and so opened the main circuit; the passage of a coin through the mechanism moved the pin and allowed the switch to close by gravity. Behind the meter register a crank pin on a disc was arranged to make one revolution during the consumption of current equivalent to the value of one coin. This crank pin periodically tripped a second lever attached to the pallet, and allowed the toothed wheels to slip back one tooth; thus, each time a coin was inserted the wheels stepped forward one tooth and each time a coin's worth of current was consumed the wheels stepped back

one tooth. The switch closed when the toothed wheels moved from the initial position and opened when they returned thereto.

5.4. Modern Types of Prepayment Meter. A great variety of types of prepayment meter have been manufactured in the past, some of which have been introduced because a special tariff has rendered the conventional type unsuitable. It is probable that with the advent in this country of nationalization of the electric supply industry, some rationalization will take place and the number of patterns in use will be reduced. The following definitions are applicable to prepayment meters which are still in use, or have been used until comparatively recent times:

1. *Single-coin prepayment meter.* A prepayment meter, the coin-freed mechanism of which is operable by coins of one denomination only.
2. *Multi-coin prepayment meter.* A prepayment meter, the coin-freed mechanism of which is operable by coins of more than one denomination. Dual-coin and triple-coin meters are common and are sometimes referred to as optional-coin meters.
3. *Single-rate prepayment meter.* A prepayment meter in which a uniform price per kWh is charged for all units consumed and the coin-freed mechanism is controlled solely by the insertion of coins and by an energy element. This type is also known as a flat-rate prepayment meter. In some cases, a manually operated device is provided, whereby the price per kWh may be changed to another value. Such meters are employed where the price per kWh varies with the season of the year.
4. *Step-rate prepayment meter.* A prepayment meter in which the coin-freed mechanism is controlled exclusively by the insertion of coins and by an energy element, and makes available the supply of a predetermined number of kWh at one given price per kWh, after which it automatically makes available any further supply at a different price (usually lower) per kWh, until the original price per kWh is restored, either manually or automatically.
5. *Load-rate prepayment meter.* A prepayment meter in which the coin-freed mechanism is controlled exclusively by the insertion of coins and by an energy element, and in which one given price per kWh is operative whenever the load (current or power) through the energy element is less than a predetermined value

and a different price per kWh is operative whenever the load exceeds that value.

6. *Two-part tariff prepayment meter.* A prepayment meter in which the coin-freed mechanism is controlled exclusively by the insertion of coins, by an energy element, and by a fixed-charge element.
7. *Two-circuit prepayment meter.* A prepayment meter in which the coin-freed mechanism is controlled exclusively by the insertion of coins and by two energy elements, or by one energy element having two current windings, and in which one given price per kWh is operative for energy supplied through one element or current winding, and a different price per kWh is operative for energy supplied through the other element or winding.

A prepayment meter of one of the types defined in paragraphs 3 to 7 above must of course be combined with one of the features referred to in paragraphs 1 and 2. Apart from the foregoing, many other types have been employed to a limited extent, and there is a distinct class used for special purposes, in which the energy element is omitted and a fixed-charge element or a time element is used instead.

5.5. The Elements of a Modern Prepayment Meter. All modern prepayment meters are of the motor type, the electrolytic types having long since become obsolete. Some are exceedingly complicated, and in addition to performing many functions, they incorporate devices which permit a wide range of adjustment to certain features and afford the user an option as to the denomination of coin which shall be inserted in order to obtain a supply of energy.

Prepayment meters have been designed for use in connection with tariffs, some of which take into consideration values other than the kWh consumed, and necessitate the use of measuring elements other than the meter itself. Accordingly, two varieties of measuring element are recognized, namely, the energy element and the fixed-charge element. In order to avoid ambiguity it is desirable to define clearly the meaning of some of the expressions used in describing the various component parts of prepayment meters.

The energy element of a prepayment meter is that portion thereof which measures or evaluates the consumption of electrical energy. In an alternating-current prepayment meter, the energy element invariably consists of an induction type watt-hour meter. In a direct-current prepayment meter, the energy element as a rule consists of an

ampere-hour meter which, strictly speaking does not measure energy but quantity. It does however evaluate the consumption in terms of kWh on the assumption that the voltage of the supply is maintained at the declared value for which the meter is calibrated.

The fixed-charge element of a prepayment meter is that portion thereof, which controls on a time basis, the coin-freed mechanism, independently of the energy element. In an alternating-current meter, the fixed-charge element usually consists of a small synchronous motor which measures time, on the assumption that the frequency of the supply is maintained constant at a declared value. In Britain where

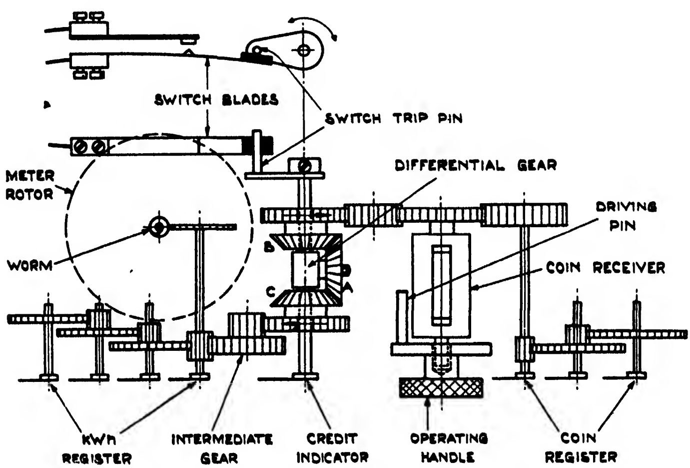


FIG. 55.—Elements of single-rate, single-coin prepayment meter.

the frequency is controlled, departure from the declared value is small under normal conditions, and any variation is compensated for daily. In a direct-current meter the fixed-charge element usually consists of an electrically-wound clock having escapement control. The driving-spring of this clock is maintained in tension by an electromagnet connected across the supply mains and energized momentarily at short intervals.

The coin-freed mechanism is the mechanism which, upon the insertion of a coin and its acceptance as indicated on the credit indicator, renders available a supply of electricity and/or reduces a debit, and which automatically interrupts the meter current circuit after delivery of the commodity in terms of electrical energy and/or time, appropriate

to the value of the coin which has been inserted. The elements of a simple form of single-rate, single-coin prepayment meter, incorporating a coin-freed mechanism and an energy element are shown diagrammatically in Fig. 55. The diagram is arranged in plan view with the elements extended in line: this arrangement is adoped in order to simplify the description, and in practice the relative positions of the parts would not necessarily be as shown.

A coin receiver, consisting of a cylinder having a slot along its axis, is arranged so that a coin inserted through the meter cover will fall into the slot and the edge of the coin will project beyond the outer surface of the cylinder. A spigot on the forward end of the cylinder carries the operating handle, which is free to turn independently of the cylinder when there is no coin in the slot. The forward end of the operating handle projects outside the meter case and can be turned by the user.

A driving pin on the handle lies close to the surface of the coin receiver and when a coin is in the slot and the operating handle is turned, say, in a clockwise direction, the driving pin will engage with the projecting portion of the coin. Further rotation of the handle will result in a corresponding rotation of the coin receiver. Suitable arrangements are made to permit the coin to fall out of, or be ejected from, the coin receiver into a coin box, after the receiver has completed half a revolution. Mounted on the rearward end of the coin receiver is a toothed wheel, arranged to drive through suitable gearing on to a coin register on the one hand, and a differential gear on the other. The coin register comprises the index or indices from which are read the figures, which permit monetary evaluation of the coins inserted.

A differential gear comprising a planet wheel A and two sun wheels B and C, is mounted on an arbor carrying the credit indicator at the forward end and a crank carrying the switch trip-pin at the rearward end. The credit indicator is the index from which is read, the figure denoting the amount of credit, or in some meters, debit. The two sun wheels B and C run freely on the arbor of the credit indicator, the wheel B being driven in a clockwise direction as indicated by an arrow. The sun wheel C is driven in an anti-clockwise direction by a train of wheels, starting from the energy element represented in the diagram by the meter rotor.

The planet wheel A runs freely on a stem projecting radially from the arbor of the credit indicator and attached securely thereto. When a coin is inserted in the mechanism and the operating handle is turned,

the sun wheel B is driven forward suddenly in a clockwise direction; this movement acting through the planet wheel A, advances the credit indicator and also moves the crank carrying the switch trip-pin (shown in elevation at top of diagram) in a clockwise direction, thus allowing the switch-blades to close and to complete the main circuit to the consumer.

The insertion of a succession of coins will increase proportionately the amount of credit indicated, and also the angular distance between the switch trip-pin and the flexible switch-blade. The consumption of current will reverse these movements until the point is reached where the value of current consumed is equal to the amount prepaid, at which point the switch will open. For the sake of simplicity in illustration, a switch which will open slowly is shown in the diagram; in practice, the tripping of the switch would take place suddenly and suitable switches will be referred to later. In addition to driving one of the sun wheels, the energy element also drives the kWh register. The position occupied by the intermediate gear shown in the diagram is usually occupied by some device for varying the price per kWh.

5.6. Choice of Coin for Operating Prepayment Meters. Prepayment meters in this country are operable by penny, sixpenny or shilling coins. Single-coin meters for penny or shilling are generally preferred to meters operated by sixpenny coins. Triple-coin meters are of course operable by penny, sixpence and shilling, and dual-coin meters by penny–shilling or sixpence–shilling combinations: it is seldom that the penny–sixpence combination is used.

Multi-coin meters were not introduced into the electricity supply industry until about 1930, although they had been used by gas supply authorities for many years prior to that date. The main reason for their use in preference to the single-coin variety is the added convenience to the user, and the assumption that this will lead to increased revenue. It is doubtful however, whether a triple-coin meter has any appreciable advantage over a dual-coin meter, in this respect; on the other hand, the use of multi-coin meters is not an unmixed blessing to the supply authority; the cost is higher than that of a single-coin meter, the space required for its accommodation is usually greater and the cost of maintenance is substantially higher. Also, the time required by the meter reader is longer, partly due to the necessity for separating the coins into two or three denominations before counting.

As regards space requirements, this factor is becoming of greater importance in small modern dwellings where passage-ways are

frequently very narrow. The practice of fixing the meter high up on the wall or over a door, necessitates the use of a chair or steps to enable the user to insert a coin and if fixed at a more convenient level, the projection of the meter is an obstruction and may interfere with the movement of bulky items of furniture. It is important therefore, to keep down the projection of the meter to a reasonable minimum and triple-coin meters in particular are at a disadvantage in this respect. The space required in the coin-box to accommodate a given value in pennies, is more than twenty times as great as that necessary to hold the same value in shillings, and this increases the overall dimensions of the meter as a rule, whether single-coin or multi-coin.

It is doubtful whether provision for the use of penny coins is justified any longer. The quantity of electrical energy now available for one penny is comparatively small and may become smaller. The cost of maintenance of prepayment meters is much higher, both in the single-coin and multi-coin types if operable by pennies, for the following reasons:—Twelve times as many pennies must be inserted as compared with shillings for the same consumption in kWh; there is a corresponding increase in wear and tear of the coin-freed mechanism and the switch. Bent and damaged pennies are frequently inserted in slot meters and these sometimes render the mechanism inoperative, whereas bent shillings are uncommon. Should the price per kWh be increased, this will in turn add to the maintenance cost owing to the increased number of coins to be inserted. The inconvenience caused to the consumer as a result of sudden interruption of the supply when credit is exhausted is more frequent where penny meters are installed. For the foregoing and other reasons, there would appear to be some justification for abandoning the use of pennies for the operation of electric prepayment meters.

5.7. Single-Rate Prepayment Meter. The single-rate (or flat-rate) prepayment meter incorporates an energy element, either direct current or alternating current, and a coin-freed mechanism which may be of the single-coin or multi-coin variety. The energy element is identical with that used in a credit meter, except for the register, which is modified to enable the gear train to be coupled to the gearing of the coin-freed mechanism. In order to facilitate the testing of the coin-freed mechanism, a disconnecting device is frequently incorporated in the gear train of the register; this device usually consists of a spring-controlled lever, movement of which, by hand, disengages one member of the gear train. This permits the coin-freed mechanism to be restored

to a zero position in a few seconds, instead of waiting for the restoration to take place through the running of the energy element, an operation which may be somewhat tedious.

The general arrangement of a single-rate, single-coin prepayment meter, is as shown in Fig. 55 on page 140. The coin receiver shown in this illustration is one of many which have been constructed, and reference is made to some of these later in this chapter: the coin register may be of the pointer or cyclometer type. Since the power for operating this register is derived from the manual operation when prepaying a coin, the objection to a cyclometer register does not arise as any excessive friction will not affect the accuracy of the energy element. The indication on the coin register is a running total, and in the case of a single-coin meter may be in terms of "total number of coins inserted" or "total value of coins". The first alternative is the more usual, and the register should be capable of showing an aggregate of 999 coins before repeating the cycle. In the case of multi-coin meters, the coins inserted may be of differing denominations and therefore the indication must be in terms of total value. An aggregate indication of 99 shillings before repeating may be regarded as an adequate minimum. The credit indicator, like the coin register, may also be of the pointer or cyclometer type and for a similar reason. The credit indication may be in terms of "number of coins", "monetary value" or "kilowatt-hours", and shows the quantity due to the consumer at any time.

The position in relation to the differential gear, of the price-change unit, for varying the price per kWh, will determine largely which of the foregoing three alternative indications is to be employed. If the price-change unit is located between the energy element and the differential, as for example in the position occupied by the intermediate gear in Fig. 55, then the credit, indication must be in terms of (i) number of coins, or (ii) monetary value. This follows because in such a case, the gear ratio between the coin receiver and the differential is fixed irrespective of the price per kWh, and consequently the advance of the index in the credit direction will be proportional to the value of the inserted coins. Thus, a single-coin meter could be arranged to indicate the number of coins or the value of the coins. A multi-coin meter taking coins of differing denominations must of necessity indicate monetary values.

If on the other hand the price-change unit is located between the coin receiver and the differential, or forms part of the coin receiving

element, then the credit indication must be in terms of "kWh unused" or "units unused", the latter term being the more usual. This follows because in such a case the gear ratio between the coin receiver and the differential will vary according to the price per kWh and consequently the advance of the credit indicator will be proportional to the value of the kilowatt-hours for which prepayment has been made.

Provision is made in some meters for what is known as a seasonal price-change mechanism. This consists of a second price-change unit together with a gear selector, which enables the supply to be paid for at one of two different prices per kWh. In some areas the supply authority endeavours to encourage the use of electricity during the summer months when the domestic load is small, by reducing the price per kWh. Thus the normal price applies during the winter months and a reduced price during the summer months. By manipulation of the gear selector which is accessible only to the meter reader, the desired price-change mechanism can be engaged twice per annum at the appropriate season. The switch and switch-trip device which is common to all types of prepayment meter will be referred to in a later paragraph.

5.8. Step-Rate Prepayment Meter. The step-rate prepayment meter incorporates an energy element, either direct current or alternating current, and a coin-freed mechanism of the single-coin variety. The coin-freed mechanism is arranged so that, during a period between two consecutive meter readings, a predetermined number of units will be available at a given price, after which any further units will be available at a different price (usually lower) per kWh. This type was in fact one of the early forms of two-part tariff prepayment meter, and the coin-freed mechanism was readily adaptable for use with either direct-current or alternating-current meters. It had a number of disadvantages under operating conditions, and although step-rate tariffs are available in many areas in this country to consumers using credit-type meters, the use of step-rate prepayment meters has been restricted in favour of other more convenient types.

A step-rate prepayment meter may be used where it is desired to collect a standing charge in addition to a running charge for current consumed. The consumer may be charged for example, 6d. per kWh for the first 60 units in each quarter after which the price may be reduced to 3d. per kWh for all remaining units; this is equivalent to a standing charge of 15s. per quarter plus a running charge of 3d. per kWh for all units consumed. The prepayment meter which is used in conjunction with such a tariff is provided with an adjustable index

which is set by the meter reader every quarter to show the number of kWh to be used at the normal (high) price. Each time a coin is passed into the meter a portion of its value is diverted to paying off a portion of the standing charge and the remainder is credited to the supply of energy. After a sufficient number of normal price units have been used to pay off the whole of the standing charge, any further consumption will be paid for at a reduced rate.

5.9. Load-Rate Prepayment Meter. The load-rate prepayment meter incorporates an energy element and a coin-freed mechanism of either single-coin or multi-coin construction. The coin-freed mechanism is so arranged that the price paid for current consumed varies according to the load. For small loads up to a predetermined limit, the cost of energy referred to hereafter as the primary rate, is higher than the secondary rate prevailing when the limit is exceeded.

The load-rate meter was introduced with the object of increasing the revenue from small consumers of electricity, particularly those who, in the past, had used energy for lighting only. These consumers were encouraged to consume more units by installing and using various electrical appliances such as kettles, irons, fires, cookers, etc. Energy is paid for at the ordinary lighting rate for the district (say 6d. per kWh), so long as the load does not exceed a predetermined amount—usually 400 watts. When the load exceeds 400 watts, a gear-change device in the meter causes a lower rate to come into operation. It is presumed that when the load exceeds the prearranged limiting value, current is being consumed for purposes other than lighting and this justifies a lower rate per kWh.

The changeover from primary rate to secondary rate is accomplished by means of an electromagnet device in series with the consumer's load. This electromagnet effects a changeover from one gear ratio to another, in a ratio gear-change unit inserted between the kWh register of the energy element and the differential of the coin-freed mechanism. An example of a load-rate meter manufactured by Metropolitan-Vickers Electrical Co. Ltd., is described in Section 6.7.

5.10. Two-Part Tariff Prepayment Meter. The two-part tariff prepayment meter incorporates a coin-freed mechanism controlled jointly by an energy element and a fixed-charge element: the majority of two-part tariff prepayment meters are fitted with mechanisms of the multi-coin variety. For use on alternating-current systems, the energy element consists of an induction type watt-hour meter, and the fixed-charge element, a small synchronous motor. For use on direct-current systems

the energy element consists of an ampere-hour meter, and the fixed-charge element, an electrically-wound clock. In both cases the fixed-charge element runs continuously, while the energy element runs at a rate proportional to the consumption of electrical energy by the consumer.

Two-part tariff prepayment meters are used where a domestic consumers' tariff is in force. Under this tariff the consumer pays a comparatively low price per kWh for energy consumed, referred to as the running charge, plus a fixed annual charge, usually assessed on the rateable value of the premises or the floor area. For convenience the fixed charge is reduced to the weekly equivalent, and all prepayment meters are scaled in terms of the weekly charge or rental. In the past the running charge in many towns has beeen ½d. per kWh and in a few cases as low as ⅜d. or ¼d. per kWh. Since nationalization of the electric supply industry however, the minimum price has been raised to ¾d. per kWh. The fixed charge varies between 6d. and 2s. 6d. per week according to the size of the premises and in some cases the fixed charge may also include hire charges for an electric cooker or other apparatus.

The first two-part tariff prepayment meter was made by Chamberlain and Hookham Ltd., and was supplied in this country in 1920. It was similar in appearance to an ordinary single-phase prepayment meter and did not incorporate a separate fixed-charge element; instead, the energy element was adjusted to run continuously, when the shunt coil alone was energized, at a rate proportional to the fixed charge it was desired to collect. When energy was being consumed, the rate of the meter was proportional to the consumption plus the fixed charge. The meter had to be calibrated for a particular value of the fixed charge and could not readily be altered except within small limits and to this extent did not meet practical requirements. The register did not indicate the actual consumption in kWh since it included the equivalent value of the fixed charge in kWh. For these and other reasons the meter was unsatisfactory and was withdrawn after a short existence, but it incorporated the basic principles which have been adopted in most two-part tariff prepayment meters which are in use at the present time.

The general arrangement of the parts of a modern alternating-current two-part tariff prepayment meter is shown in Fig. 56. The energy element indicated by a meter rotor and the fixed-charge element indicated by a synchronous-motor rotor, both drive through intermediate gears on to the sun wheels of a differential gear (1), the direction of driving the sun wheels being indicated by arrows. The summation

of these movements is collected and transferred through gearing to one sun wheel of a second differential (2). The other sun wheel of this differential is actuated by the insertion of coins in the coin receiver and again the direction of driving is indicated by the arrows. This second differential corresponds to the differential in an ordinary single-rate prepayment meter, being actuated in the credit direction on the insertion of a coin, and in the debit direction by the consumption of energy and/or the lapse of time.

Between each of the two driving elements and the first differential gear suitable devices are incorporated at the positions occupied by the

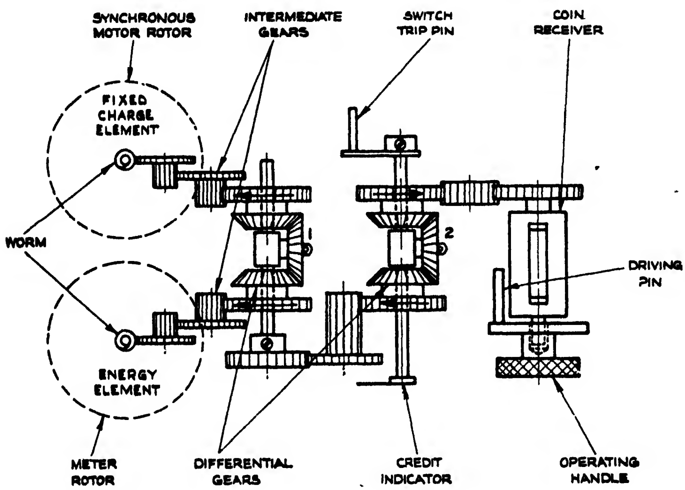


FIG. 56.—Elements of two-part tariff prepayment meter.

intermediate gears, to enable the price per kWh and the weekly fixed charge to be varied as desired. It will be appreciated that the diagram is drawn in a simple manner to show the principle of the mechanism, whereas in fact, the actual devices for these purposes are much more complex than indicated.

There is an important difference in the functioning of a two-part tariff prepayment meter as compared with a single-rate meter, due to the action of the fixed-charge element. The latter runs continuously, even after the switch has opened and has interrupted the supply of current to the consumer. Provision must therefore be made for the credit indicator to travel below zero and to indicate a debit if there is

failure to insert a coin immediately the switch has opened; this contingency is likely to arise, if for example the premises are closed due to the occupier being on holiday, and may also occur for other reasons. When a debit is indicated a sufficient number of coins must be inserted to cancel the debit, plus one coin to establish a credit, before the switch will reclose and render available a further supply of energy.

In extreme cases where the premises may be untenanted for a long period, there is a risk that the debit incurred may exceed the provision made for its registration on the indicator. Since the fixed-charge element is running continuously the time will arrive when the index reaches the end of its travel. It is usual to incorporate in the gear train a clutch device which can slip at this point in order to prevent damage to the mechanism or stripping of the gears at the slow-moving end of the train. One alternative to this is to provide a debit scale of such magnitude that under no likely circumstance will the end of the scale be reached; another alternative is to fit in series with the synchronous motor, a switch which opens when the index reaches the end of the scale, thus stopping the motor.

In early patterns of two-part tariff prepayment meter made by Chamberlain and Hookham Ltd., a device was incorporated which permitted a consumer to obtain a limited amount of energy on the insertion of one coin only, even though he had not thereby cleared the whole of his debit. For example, if a debit of five shillings had been incurred, the consumer could, by the insertion of one shilling, obtain immediately energy to the value of twopence, while cancelling debit to the value of tenpence. This was a convenience to the consumer who might have insufficient coins of the correct denomination to cancel the whole of his debit and also to establish a credit. Because this principle was not universally acceptable to supply undertakings, the manufacture of the device was discontinued.

5.11. Two-Circuit Prepayment Meter. The two-circuit prepayment meter incorporates a coin-freed mechanism controlled jointly by two energy elements or by one energy element having two current windings. The object of this type of meter is to enable a supply of electricity to be provided at two different flat rates. For example, a consumer may obtain a supply of energy through a single meter for lighting purposes at a comparatively high price, say 6d. per kWh, and for heating or the like at a much lower price such as 1½d. per kWh.

In its original form, this meter was provided with an energy element having two current windings, one for the lighting circuit and the other

for the power. Two alternative arrangements of the windings were available according to circumstances and these are shown in Figs. 57 and 58. In Fig. 57 the two windings are in series and current for the lighting circuit passes through both. For the power circuit, a tapping is provided and current for this circuit passes through a portion of the winding only. Thus, a current of any particular value passing through the power winding will result in a lower rate of registration than if passed through the lighting winding. The ratio—lighting price/power price—must be determined when ordering the meter and cannot be adjusted to any other value. This ratio determines the relative number of ampere-turns on the two windings. The current ratings of the windings may be different as for example 2·5 or 5 amperes for the lighting circuit and 10 amperes for the power circuit.

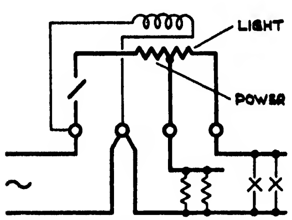


FIG. 57.—Two-circuit prepayment meter with tapped current winding.

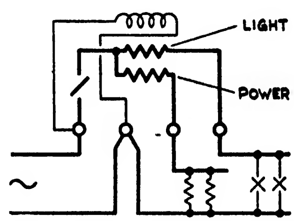


FIG. 58. Two-circuit prepayment meter with paralleled current windings.

The other alternative arrangement of current-windings shown in Fig. 58 consists of two separate windings arranged in parallel, the one carrying the current for the lighting circuit only and the other, current for the power circuit only. As in the first arrangement, the ratio of the prices for current determines the relative numbers of ampere-turns on each winding. Although it is not possible to alter the ratio of the prices per kWh, it is possible to raise or lower the actual prices. For example, if the original price of current was 5d. per kWh for lighting and 1¼d. per kWh for power, giving a ratio of 4/1, these prices could be raised to 6d. and 1½d. respectively or lowered to 4d. and 1d., thus maintaining the same ratio. The price variation is accomplished by means of a simple price-change gear unit and the same range of prices are available as for an ordinary single-rate prepayment meter. The range of price ratios is restricted and it is not possible to obtain every desired combination, but ratios such as 2/1, 3/1, 4/1, 5/1, and 6/1 are usually possible.

Before the advent of the two-part tariff prepayment meter, the forms of two-circuit prepayment already described were used by numerous supply undertakings. They had one drawback, however, and because of this, the Electricity Commissioners withheld their approval of the type; if the register was geared to show correctly the kWh consumed in the lighting circuit, it would show only a portion of the consumption in the power circuit, the amount depending upon the ratio of the prices. Thus, if the lighting price was 6d. per kWh and the power price was 1½d. per kWh, consumption in the lighting circuit would be registered correctly, but only one-quarter of the power consumption would be registered.

To overcome this objection, a more elaborate form of two-circuit prepayment meter was introduced, having two separate energy elements each fitted with its own register. This gave the actual consumption in each circuit, the connections being as shown in Fig. 59. The arrangement of the coin-freed mechanism is identical with that of a two-part tariff prepayment meter as shown in Fig. 56, the two energy elements taking the place of one energy element and one fixed-charge element. A further advantage of this meter as compared with the older forms is that the price per kWh for which each element is geared can be altered independently, and also each element can be supplied for any standard current rating.

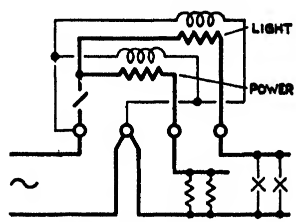


FIG. 59.—Two-circuit prepayment meter having two separate energy elements.

5.12. Differential Gears in Prepayment Meters. All prepayment meters, with the exception, perhaps, of the electrolytic types which are obsolete, incorporate some form of differential gear. The commonest form is that illustrated in Figs. 55 and 56 comprising three bevel wheels, two of which are co-axial and are referred to as the sun wheels. The third, which meshes with the other two and is mounted freely on a stem at right angles to the differential shaft is referred to as the planet wheel. In a single-rate prepayment meter the two sun wheels revolve in opposite directions, the one moving only when coins are inserted and the other when energy is being consumed. The planet wheel revolves on its stem and carries the differential shaft back and forth, in the credit direction when coins are inserted and in the debit direction when energy is consumed. The function of the differential is to indicate

the state of the credit and to control the opening and closing of the switch.

The forward end of the differential shaft carries a pointer moving around a fixed scale showing the amount of credit, and the rearward end carries a crank with a switch trip-pin as shown in the illustrations, or alternatively and more commonly, a cam which, according to its position, serves to hold the switch in the closed position when credit is established, or to release the switch when credit is exhausted.

In the gear train between the rotor of the energy element and the driving pinion or wheel on the coin receiver, a certain amount of backlash is inevitable and the effect of this, if uncorrected, would be to introduce some uncertainty in the tripping of the switch. To eliminate this uncertainty a spring is introduced, acting on the differential shaft and tending to assist the energy element. The tension on this spring is derived from the manual operation when a coin is passed through the mechanism. This has the added advantage that the energy element is relieved of the necessity of driving a considerable amount of extra gearing, the friction of which might otherwise introduce errors, particularly on low loads, in the registration of the energy consumed.

A variation in this form of differential which is frequently employed is an epicyclic gear comprising two co-axial spur wheels functioning as sun wheels and a radial arm moving between them carrying at its extremity a cage with two meshing planet pinions. The one pinion engages one of the sun wheels and the other pinion engages the other sun wheel. In other respects, this differential acts in a manner similar to the one first described.

A second form of so-called differential which is used to a small extent comprises a shaft, corresponding to the differential shaft, and having a screw-thread running along its length. Running freely along the screwed shaft which is driven by the meter is a nut having a radial slot. Engaging with the slot is a long pin projecting axially from a wheel running freely, but without axial movement, on a plain portion of the shaft; the wheel is driven from the coin receiver. When a coin is inserted in the meter the wheel with its driving pin is rotated on the stationary shaft and a corresponding angular movement is imparted to the nut; the latter moves axially along the shaft and this movement permits the switch, after closure, to be retained in the closed position.

When energy is being consumed the screwed shaft is rotated by the energy element, and the nut which cannot turn independently of its driving-pin is caused to return along the shaft towards its initial

position. When the nut reaches the end of its travel in the debit direction it actuates the switch-release mechanism and the consumer's circuit is opened. The credit indicator consists of an index finger mounted on the forward end of the screwed shaft and a revolving scale concentric therewith driven by the inserted coins. Thus the insertion of a coin or coins moves the scale in the credit direction. Consumption of energy causes the index to follow in the same direction, thus cancelling the credit indication.

A third form of differential also has a revolving scale and a following index. A shaft driven by the meter revolves inside a sleeve driven by the inserted coins; the forward end of the shaft carries an index and the forward end of the sleeve carries a scale. The rearward end of the sleeve has a disc mounted thereon, having a depression on its surface at one point. Co-axial with and adjacent to the disc is a wheel mounted on the shaft which is driven by the meter. This wheel carries a pivoted lever arranged radially and the free end of the lever has a small roller attached which is pressed against and rides on the surface of the disc. When the credit is exhausted, the roller rests in the depression on the surface of the disc and the index then coincides with the zero on the scale.

The insertion of a coin or coins rotates the disc and causes the small roller to rise out of the depression on its surface; the scale also rotates and indicates the state of credit. Then the lifting of the roller and the corresponding movement of the lever serves to actuate the mechanism which retains the switch in the closed position. The consumption of energy causes the meter-driven shaft to follow on in the same direction as the sleeve, cancelling the credit indication; the roller rides on the surface of the disc until it reaches the depression at which point the roller drops into the depression and the lever on which it is mounted actuates the mechanism which releases the switch.

5.13. Prepayment Meter Switch. The earliest types of prepayment meter were fitted with mercury switches consisting of two cups containing mercury which were bridged by a copper stirrup in the closed position, the stirrup being withdrawn to open the consumer's main circuit. In those days direct-current supplies predominated and the maximum current handled by the switch seldom exceeded five amperes. The modern prepayment meter may be called upon to deal with currents up to fifty amperes at 240 volts or thereabout and alternating-current supplies predominate.

When used on a direct-current circuit, the current-interrupting

capacity of a switch is very much smaller than when used on an alternating-current circuit and in fact some switches are quite unsuitable for direct-current circuits. The original form of mercury switch has been considerably modified and in an improved form is still used by one or two manufacturers of alternating-current prepayment meters for currents up to fifty amperes. A mercury switch is also used by one manufacturer of direct-current prepayment meters for currents up to forty amperes; the majority of meter manufacturers however, use some other type of switch.

Closure of the switch in a prepayment meter is usually effected by manual operation. If the switch is in the open position, the passage through the mechanism of the first coin to establish a credit, must effect closure. In the case of a two-part tariff prepayment meter which has run into debit, the insertion of several coins may be necessary before the debit is cleared and credit established. The power required to close the switch is usually derived from a spring, which is extended (or compressed) and is then suddenly released by the action of the consumer in passing a coin through the mechanism. As a rule it is not possible for the consumer to effect closure while the coin in the mechanism is still under his control and this is ensured by some form of cam action on the coin receiver which pushes or throws the switch into the closed position at the instant when the coin is ejected from the coin receiver into the cash box. A latching device retains the switch in the closed position until credit is exhausted.

Opening of the switch is effected by the energy element or, in the case of a two-part tariff prepayment meter, by the energy element and the fixed-charge element acting jointly through the differential gear. In order that the burden imposed on the meter due to the tripping of the switch may have little effect on the low-load accuracy, the power required for this operation must be kept to a low value. At the same time, the switch must remain in the closed position so long as credit remains, and must not be liable to be tripped out due to vibration or shock. Spring tension acting on the differential shaft in the same direction as the meter drive, tends to relieve the energy element of the effort required to trip the switch when credit is exhausted. It is desirable that the tripping mechanism shall have a smooth action, otherwise variations are likely to occur in the amount of energy delivered for each coin inserted. Any undue friction in this mechanism will be revealed if a succession of coins are passed through, one at a time, and the amount of energy delivered for each coin is observed.

It may be noted that some variation in the apparent kWh per coin must be expected, particularly in a direct-current meter having a relatively low driving torque and no means of compensating for friction. The magnitude of the variation in a meter which is in good mechanical condition will depend upon several factors, the most important being: (1) the current rating of the meter, (2) the denomination of the coin inserted and (3) the price per kWh for which the meter is geared. The higher the current rating, the smaller the denomination of the coin and the higher the price per kWh, the more difficult will it be for the meter to maintain consistency. The two following examples will serve to illustrate this point.

Example 1. A 25-ampere 240-volt prepayment meter is arranged to take penny coins and is geared for a price of 6d. per kWh. The rotor makes 24 r.p.m. at full load, which is equivalent to 240 revs. per kWh. If pennies are inserted, one at a time, and the meter is run until the switch opens before another penny is inserted, the rotor should make 40 revolutions for each coin.

Example 2. A 5-ampere 240-volt prepayment meter is arranged to take shilling coins and is geared for a price of 1d. per kWh. The rotor makes 24 r.p.m. at full load which is equivalent to 1,200 revs. per kWh. Since one shilling will provide for 12 kWh, the rotor should make 12,000 revolutions for each coin inserted.

Comparison of these two examples, which represent extreme cases in order to emphasize the point, shows that the burden imposed on the meter in the first case is relatively onerous, since the disturbing effect of unlatching the switch is concentrated over 40 revolutions of the rotor, while in the second case it can be distributed over 12,000 revolutions. It should be obvious that some allowance must be made to cover possible variations in the apparent kWh per coin, where tests are made to ascertain the amount delivered per coin for a succession of coins. In an extreme case such as in Example 1, variations of 10 per cent. or more might be found between the amounts delivered for a succession of single coins, whereas in Example 2, the variation might be almost imperceptible.

Lest it be assumed that errors of alarming magnitude are to be expected in prepayment meters under these adverse conditions, let it be emphasized that these variations are of little practical importance. It is true that a consumer having a penny-operated meter, may make comparisons between the hours of lighting of a single lamp per penny for a succession of pennies, and may observe a variation, but if for one

coin there is a shortage, this will probably be made good by an excess on the succeeding coin. The amount in kWh delivered to the consumer is determined mainly by the gearing between the meter rotor and the switch-tripping mechanism and provided that the gear ratio is correct, the error due to variation in switch tripping taken over an interval of a week or more will have disappeared entirely. The variation is much less noticeable in a shilling-operated meter than in a penny meter.

5.14. Coin Receivers in Single-Coin Meters. The coin receiver in a prepayment meter is a very important component and one which is subject to much abuse. It is desirable that its operation by the user shall be simple and foolproof. It must discriminate between suitable and unsuitable coins and it must as far as possible defeat attempts to actuate the credit mechanism in a fraudulent manner. It must also be robust in order to withstand the rough treatment to which it is subjected by some consumers and so constructed that coins which have actuated the mechanism cannot be extracted through the coin entry.

The constructional details of coin receivers differ widely but all have one feature in common namely, that discrimination between suitable and unsuitable coins is based on diameter and not on thickness or weight. Coins of any particular denomination as minted in this country are reasonably uniform as regards diameter and thickness. Worn coins however vary considerably in thickness and weight and among pennies, an old coin may be as much as 40 per cent. thinner than a new one. The variation is less than this amount in the case of shillings and sixpences. Variation in the diameter of coins of all denominations, new and worn, is comparatively small and accordingly this feature may be regarded as the most suitable for discriminating between a correct and an incorrect coin. Bent and damaged coins are uncommon in the silver denominations but are frequently encountered amongst pennies, and because of this, mechanisms which have become inoperable are more common when the operative coin is a penny.

For a single-coin meter the test applied to a coin to ascertain whether it is of the correct denomination usually takes the form of two simple gauging operations. The slot in the casing of the meter through which the coin is passed into the coin receiver is of such a length and width that a new coin of correct denomination will just pass through; any coin of greater diameter or thickness will be rejected. A coin which is accepted by the first gauge passes into the coin receiver and falls on

to two pegs or projections so spaced that a coin of correct dimensions cannot pass between them; a coin which is undersized however, will pass the barrier and fall into the coin box without operating the credit mechanism. A coin receiver of this type is shown in Figs. 55 and 56.

The next operation consists in turning an operating handle which projects through the cover of the meter; this causes a driving pin to revolve around the coin receiver and to engage the edge of the coin. Further rotation of the driving pin causes the coin to act as a transmission member, rotating the coin receiver and advancing the credit mechanism and coin register. On completion of a half-revolution or thereabouts of the coin receiver the coin falls or is ejected into the coin box, and the meter switch if not already closed is moved into the closed position.

Some device is usually incorporated which, when a coin is in the receiver, prevents the entry of a second coin by interposing some obstruction in its path, the obstruction remaining until the first-mentioned coin has been discharged; a similar device comes into operation when the number of coins prepaid reaches the maximum for which the mechanism is constructed; frequently this consists of a shutter which closes the coin entry and does not re-open until the credit has been reduced below the maximum value. In lieu of this shutter some manufacturers make the credit reserve so large that it is very unlikely the consumer will prepay coins sufficient in number to necessitate closure of the coin entry.

An alternative method of rejecting undersize coins consists in so arranging the coin receiver that a coin on entering moves a lever which can engage with a toothed wheel, and when in engagement can act as a transmission member between the operating handle and the credit mechanism. A coin which is too small will fail to move the lever a sufficient distance to engage the toothed wheel and on rotating the coin receiver the coin will eventually fall out or be ejected into the coin box without actuating the credit mechanism. A coin receiver of this type is shown in the illustration of a meter manufactured by Smith Meters Ltd., in Fig. 66.

5.15. Coin Receivers in Multi-Coin Meters. The coin receivers in multi-coin meters supplied by different manufacturers differ widely in their construction and method of operation. In some types a single coin entry is provided through which all coins are inserted, irrespective of their denomination; in others a separate coin entry is provided for each denomination and the consumer must take care to insert the coin

in the appropriate slot. The latter method is perhaps the simpler as regards the construction of each coin receiver but sometimes occupies more space, particularly in the triple-coin mechanisms, and this may result in a somewhat larger case.

The majority of makes of multi-coin prepayment meters are of the single-entry type and since coins of varying diameter pass through the same slot, the gauging of the coin must of necessity be carried out after entry; usually this operation is performed in the coin receiver. In the event of a coin of incorrect denomination being inserted through the slot this should not operate the mechanism and means must be provided for the disposal of the coin. In some cases a coin of incorrect diameter is returned through the coin entry, but if accepted at this point and passed to the coin receiver it should be possible to turn the operating handle and release the coin into the coin box without advancing the credit mechanism, or preferably the coin should be returned to the consumer through a suitable outlet. In many types of meter, the operating handle cannot be turned when an incorrect coin is in the receiver, and release is effected by pressing a button which allows the coin to fall, either into the coin box or through an outlet from whence the consumer can recover it.

Prepayment meters which are made with a separate coin entry for coins of different denominations may have two slots for pennies and shillings respectively or three slots for pennies, sixpences and shillings. In some cases the coin entry provides the gauge for the maximum diameter of the coin for which it is appropriate and the receiver effects disposal of undersize coins; in other cases devices are provided for preventing the entry of undersize as well as oversize coins. Owing to the diversity in the methods of discriminating between acceptable and unacceptable coins some further reference to coin receivers is made in a later section dealing with specific types of prepayment meter.

5.16. Unit Price-Change Mechanisms. Means must be provided in prepayment meters for varying in a convenient manner, the price per unit or per kWh, to meet the requirements of the tariff in force for the time being. In the past the variation in the prices charged per kWh has been considerable. Prepayment consumers, who have received a supply for lighting purposes under a flat-rate tariff, have been charged prices lying between the extremes of 3d. and 1s. per kWh, the majority being in the region of 4·5d. per kWh. Consumers receiving a supply under a domestic two-part tariff have paid, in addition to the standing charge, a price per kWh varying between the extremes of 0·25d. and 2d., the

majority paying 0·5d. or thereabouts. The minimum charge in the future may be expected to be 0·75d. per kWh under the domestic two-part tariff.

Changes in price per kWh are not frequent, but when a change is made which affects prepayment consumers, it usually involves alterations or adjustments to the mechanisms of very large numbers of meters, which alterations must be effected in a comparatively short time. The cost of making the alterations must also be kept within reasonable limits and it is essential that the change can be made by unskilled or semi-skilled labour, without risk of interfering with the accuracy of the meter.

There are two distinct methods of varying the price per kWh; in the one the variation is made by changing the gear ratio between the energy element and the meter-driven side of the differential gear. In the other the gear ratio is changed between the coin receiver and the coin-driven side of the differential. These possibilities will be understood more readily by reference to Fig. 55. If the first of these alternatives is adopted, it will be obvious that a change in the gear ratio between the energy element and the differential, say, by an alteration in the intermediate gear, will result in a corresponding change in the rate at which the credit indicator is run down due to the consumption of electrical energy. The indications on the credit indicator will be in terms of "number of coins unused" or "money value unused", i.e. shillings and/or pence. If the second alternative is adopted a change in the gear ratio between the coin receiver and the coin-driven side of the differential will result in a corresponding change in the advance of the credit indicator, due to the insertion of one coin; in this case the indications on the credit indicator will be in terms of "units unused" or "kWh unused".

In the early types of prepayment meter developed in this country, the unit price-change was usually effected by the exchange of a wheel and pinion in the gear train between the energy element and the differential for a pair giving a different gear ratio. An alternative method involved the exchange of one price wheel and the movement of a pinion mounted on a hinged lever, to gear up with the altered diameter of the new price wheel. These methods necessitated the removal of the meter cover and also in some cases the removal of the energy register. The correct meshing of the new gears called for a certain amount of skill on the part of the operator and as the work had to be carried out on consumers' premises, possibly in an inconvenient and badly-lighted situation, the method could not be regarded

as satisfactory. This was followed by the introduction of a price-change unit or price compound consisting of a small train of wheels mounted between two plates and capable of being removed and replaced in a very simple manner. By slackening off one, or maybe two screws, the price-change unit can be detached and replaced by a new one; on tightening up the screw or screws the unit is automatically located in the correct position and no skill is required on the part of the operator to ensure correct meshing of the gears. This method is in use in many types of prepayment meter in current production and a suitable price-change unit can be provided to cover exactly any desired price per kWh within a very wide range.

Another method of altering the price per kWh is by changing the gear ratio between the coin receiver and the differential. This follows on the practice which is adopted in gas meter construction of combining the price-change element with the coin receiver itself. The coin receiver is mounted on the back of a removable circular metal plate, referred to hereafter as the price-change plate; this plate has a number of serrations evenly spaced around the greater part of its circumference and forms the cover to a pocket in the casing of the meter. A radial slot in the price-change plate forms the entry to the coin receiver and an operating handle projecting through the centre of the plate enables the coin receiver to be rotated through a limited arc, independently of the plate.

In the back of the pocket is a toothed wheel geared to the coin-driven side of the differential; the angular spacing of the teeth on this wheel is the same as the angular spacing of the serrations in the price-change plate. The coin exit from the receiver is at the bottom of the pocket, but the position of the coin entry can be varied by rotation of the price-change plate. A fixed pin in the circumference of the pocket engaging with one of the serrations serves to locate the price-change plate in any selected position and determines the arc through which the coin-receiver moves between the entry and the exit of the coin. The entry of the coin couples the operating handle to the toothed wheel in the back of the pocket and turning of the handle imparts a corresponding movement to the wheel. Discharge of the coin from the receiver uncouples the operating handle which can then be returned to its initial position, at which a further coin may be inserted.

The number of serrations in the circumference of the price-change plate is usually thirty-six or more, and by altering the position of the plate in the pocket a corresponding number of variations in the arc of

advance communicated to the coin-driven side of the differential gear can be effected. The greater the angle through which the coin travels between entry and discharge the greater will be the amount of energy available per coin inserted. Alteration in the position of the price-change plate is effected after removal of the coin-box and this operation is readily performed by the meter-reader; replacement of the coin-box prevents alteration in the position of the plate by unauthorized persons.

This method of varying the price per kWh differs from the price-compound method in that it gives uniform advances in terms of "kWh per coin" and not in "pence per kWh", the one expression being proportional to the reciprocal of the other. Because of this difference many of the available steps result in odd fractions such as, for example, 2·93 pence per kWh. While a wide range of variations is possible, many of the steps correspond to values which will never be required. The prices charged by Area Boards usually vary in steps of a farthing or a halfpenny per kWh for the higher prices, and for prices below one penny, in steps of one-eighth or one-tenth of a penny. If the correct price cannot be selected from those available on the price-change plate, the next higher price is selected and a rebate is given to the consumer each time the coin box is cleared.

In addition to the foregoing methods of varying the price charged for energy, some manufacturers incorporate a mechanism which permits an adjustment to be made by a variable gear device. Usually this consists of a cone of gear wheels of varying numbers of teeth mounted on a shaft, the axis of which lies parallel to a long pinion. Mounted on the pinion is a carriage which can be moved from end to end and pivoted in the carriage is a jockey wheel; the latter is always in gear with the pinion, and by sliding the carriage along, the jockey can be engaged with any selected gear wheel in the cone. An indicator-plate shows the price per kWh corresponding to each position of the carriage.

The usual position for this variable gear is between the energy register and the differential, consequently the scale shows the price per kWh. One manufacturer provides two cones of wheels, selection from the one giving steps of one penny per kWh and from the other, steps of one-eighth of a penny per kWh. By the use of the two cones, any price between 10d. per kWh and ⅛d. per kWh in steps of ⅛d. per kWh can be obtained; the variable-gear unit is accessible through a hinged window which can be sealed after an adjustment has been made.

5.17. Fixed-Charge Elements. The function of the fixed-charge element in a prepayment electricity meter is to integrate the amount due from the consumer for that portion of the cost of the supply which is independent of the consumption of current; this takes the form of an annual charge, frequently based on the rateable value of the premises or the floor area, and for convenience in metering is considered as a weekly sum. The amount varies in practice between 6d. and 5s. per week according to the size and situation of the premises, and may include, in addition, the hire charges on an electric cooker, water heater and various electrical appliances. In some cases the sum of 10s. per week, or even more, is registered by the fixed-charge element. The fixed-charge element is usually associated with an energy element in a two-part tariff prepayment meter.

Reference has already been made to the first two-part tariff prepayment meter in which the energy element and the fixed-charge element were combined, the fixed charge being integrated by causing the energy element to register at an appropriate rate when no current was being used by the consumer; the limitations of this meter were soon evident and the functions of the two elements were separated. The early types of fixed-charge element consisted of a small shaded-pole motor driving through a train of wheels to a differential gear which summated the registrations of the energy and fixed-charge elements and transferred the sum to the debit side of the differential in the coin-freed mechanism. The fixed charge was adjusted to the required amount by varying the speed of the motor; the latter being energized by connection across the supply mains. The motor speed was subject to errors arising from variation in voltage, frequency and temperature, and the magnitude of the error was not negligible. Following the interconnection of electricity generating stations and distribution systems in this country by the Central Electricity Board, frequency control became possible and small synchronous motors were then developed for operating time-keeping devices. These motors took the place of the shaded-pole motors and as departures from the standard of frequency were corrected daily, a means of accurately registering the fixed charge became available.

All fixed-charge elements for alternating-current prepayment meters now incorporate a small synchronous motor, running at a constant speed for constant frequency and driving a train of wheels which includes a device for varying the amount registered. The motor is arranged to run continuously but by periodically interrupting the transmission between motor and coin-freed mechanism during a time

interval which is capable of adjustment, the amount of the weekly fixed charge can be varied to the requirements of each individual consumer. The fixed-charge element in a direct-current prepayment meter is not quite so convenient as its alternating-current counterpart since there is no simple equivalent to the synchronous motor as a time element. In this case an electrically-wound clock is employed and the usual method for varying the fixed charge to be collected is to employ a small gear compound. This is positioned between the clock and the coin-freed mechanism and arranged conveniently for removal and replacement when it is desired to alter the amount of the fixed charge.

Various methods have been adopted by different manufacturers to convert the constant-speed drive from the synchronous motor into a variable-speed drive on to the differential which summates the total debit from the energy element and the fixed-charge element. The principle involved, however, is similar in the majority of cases; the motor drives a train of wheels terminating in some form of clutch, which may be a pawl or a friction drive. Periodically the clutch is disengaged and the motor runs freely without driving the coin-freed mechanism; after an interval the clutch is re-engaged and the drive continues. This cycle is repeated indefinitely. The disengagement and re-engagement of the clutch is accomplished by two stops, one fixed and the other adjustable; the latter is associated with a scale and index which indicates the amount of the fixed charge. Provision is made for setting the adjustable stop and its associated index without removal of the meter cover. Operation of the setting device by unauthorized persons is prevented by a seal or, in some cases, by making the device accessible only when the coin box is removed.

An example which illustrates one application of the foregoing principle consists of an arm rotated continuously by the synchronous motor and carrying a pawl at its extremity. The pawl is retained in position by friction and has two tails, one of which meets a fixed stop once in each revolution of the arm, the other meeting an adjustable stop. A ratchet wheel is mounted co-axially with the rotating arm, and when one tail of the pawl passes the fixed stop, the pawl is pushed into engagement with the ratchet wheel which is then carried round by the arm; as the other tail of the pawl passes the adjustable stop, the pawl is disengaged from the wheel which then remains stationary until the next cycle of operations commences. The ratchet wheel is geared to the differential which summates the total debit and it will

be obvious that the longer the period over which the pawl is in engagement with the ratchet wheel during each revolution, the greater will be the amount of fixed charge debited to the consumer.

In another application of this same principle an arbor rotated continuously by a synchronous motor carries an arm having a spring-controlled pawl at its extemity. Once in each revolution of the arm the tail of the pawl engages an adjustable stop, in passing which, the pawl is displaced but returns to its normal position under spring control. Mounted on the same arbor but not secured thereto is a second arm which normally is held against a fixed stop by spring tension. This second arm carries a pawl which engages with a ratchet wheel loosely mounted on the arbor and the extremity of the arm carries a long pin lying in the path of the pawl on the rotating arm. As the latter moves around, the pawl on its extremity meets the long pin projecting from the extremity of the second arm and the two then rotate together. The pawl on the second arm pushes around the ratchet wheel which in turn is geared to the differential summating the total debit. In due course, the pawl on the rotating arm meets the adjustable stop and is deflected; this action releases the second arm which flies back against the fixed stop. The amount of rotation communicated by the synchronous-motor drive to the ratchet wheel depends upon the angular distance separating the two stop pins.

5.18. Comments on Prepayment Meters in General. Several matters concerning prepayment meters in general may usefully be considered at this stage. The question as to the possibility of fraudulently manipulating the coin-freed mechanism is one which receives consideration from designers and purchasers alike, to say nothing of a small proportion of the actual users. Some purchasers of prepayment meters derive entertainment in attempting to devise methods of so manipulating a prepayment meter (in the test-room of course) that a supply of energy can be obtained, either without inserting a coin, or by making a coin deliver more energy than the correct amount, or by extracting the coin after insertion. Designers, too, are well aware of some of the methods adopted to this end, and before a coin-freed mechanism is put on the market, it is subjected to careful examination in order to ensure that it is reasonably fraud-proof. It is not proposed to reveal any of the devices which can be adopted in order to obtain a supply without paying for it in full, but it is probably true to say that after a careful study of a coin-freed mechanism, supplemented by previous knowledge of fraudulent methods, an ingenious meter engineer can usually

devise a method of defrauding the mechanism. A prepayment meter is in no way superior in this respect to a safe, and as is well known, the doors of many complicated safes have been opened without a key by locksmiths and other individuals who have made a study of their mechanisms.

Without a knowledge of the constructional details of any particular prepayment meter it is difficult for a consumer to discover a method of defrauding, and so far as he is concerned he is limited to the use of spurious coins or checks, or to information which may be passed to him by someone with a knowledge of meter construction. As regards the use of checks and discs having approximately the same diameter as the correct coin, these will actuate the mechanism in a normal manner and will be found in the cash-box when the meter-reader makes the periodical collection. Since these can have been inserted only by the consumer or some person acting on his behalf, and since the energy received in exchange has been used on the premises, no difficulty should arise in obtaining the correct coins from the consumer in exchange for the false. In this respect, a prepayment meter is in a different category from an automatic delivery machine, access to which is available to all and sundry. If a spurious coin is inserted in such a machine it will usually be difficult to identify the person responsible unless he is caught in the act.

Prepayment consumers have been known deliberately to make use of a button or disc of suitable dimensions, in order to obtain a supply of energy in an emergency, when no appropriate coin has been available, and have readily tendered the correct coin when, at a later date, the coin-box has been cleared. This practice is regarded as perfectly legitimate by most supply authorities. As regards other methods of fraudulent manipulation, it is not reasonable to expect a manufacturer to undertake costly re-design in order to circumvent a method which has been practised by a consumer in an isolated case. A simple remedy in such a case would be to change the meter in the premises of this consumer and to install an entirely different type which would not respond to the particular method of fraud which had been practised.

Periodically a demand arises for a prepayment meter fitted with a device which will give a warning that the switch is about to open and cut off the supply of current. The demand is accompanied by a harrowing story of a mother bathing her baby when the light is extinguished or of the predicament of a housewife who discovers that the Sunday joint is only half-cooked when meal-time arrives, because the supply

has been cut off without her knowledge. Usually the demand comes from an engineer (not the meter engineer) who has applied for a patent and wishes to exploit his invention. The patent records include numerous examples of abandoned patents for this particular object and as a rule there is no difficulty in modifying a prepayment meter in order to give a warning. In every case, however, the cost of the meter is increased and few purchasers are prepared to pay the additional price which must include the cost of the bell, buzzer, or other audible signal, battery or mains-operated. An audible warning which chances to operate when the last member of the family is retiring for the night may prove to be more of a nuisance than a convenience because the noise will continue until a coin is inserted or the switch opens. If consumers would observe from time to time the state of the credit indicater fitted to all prepayment meters the supposed necessity for a warning device would disappear. A consumer who habitually allows the switch to open before inserting another coin has no one to blame but himself for any inconvenience caused thereby.

It is customary for the coin-box of a prepayment meter to be padlocked in order to prevent pilfering of the contents; the padlocks are provided by the supply authority, and the cost of these must represent a substantial sum of money where large numbers are in use. Unfortunately there is no standard padlock for this purpose. The type of padlock used by some undertakings is changed from time to time, and frequently, it is to be feared, without full consideration being given as to the suitability of the new padlock for the prepayment meters. As a result of such a change, meter manufacturers sometimes receive a request that the hasp or other device fitted to the meter for the reception of the padlock shall be altered to suit the new one, and this they must do although the cost of the alteration may be in excess of the cost of the padlock. Failure to accede to the request may result in the loss of the business.

It is questionable whether the capital outlay on padlocks is justified in the first place as an insurance against loss of the contents of the coin-box. In many types of meter, access to the money in the coin-box can be obtained by removal of the meter seals and withdrawal of the cover. If a burglar wishes to obtain access, he may break open the meter case, causing damage to the value of many padlocks. It has been stated by one supply undertaking that the use of seals instead of padlocks has resulted in considerable saving. A continental practice is to provide a sealing pin to pass through the hasp of the meter and to seal this pin

against withdrawal. The contents of the cash-box are then just as safe as if secured by a padlock, so far as interference by the consumer is concerned and a burglar will find it easier to remove a seal than to burst open the case, thus avoiding the cost of repairs in addition to loss of the contents. It is therefore suggested that the adoption of sealing would be better and cheaper than the present somewhat unsatisfactory arrangement.

5.19. Accuracy of Prepayment Meters. The limits of error in a credit meter are laid down in B.S. 37: 1937, Clause 37. These limits are comparatively small and are based on the assumption that the friction in the register and the rotor bearings is negligible. No allowance is made for any extraneous disturbing influences which may result in an increase in friction, but it is recognized that the combination with an energy element of a coin-freed mechanism may, and probably will, influence the accuracy of the energy element, particularly on low loads. Accordingly the specification permits an increase in the limits of error for prepayment meters, and the relevant sentence in Clause 37 may be paraphrased thus: "The limits of error for 5 per cent. marked current D.C., or A.C. at unity power-factor, or 10 per cent. marked current at 0·5 power-factor (lag.), shall be subject to an allowable increase of $\pm$ 1·0 per cent." The effect of this extension to the limits of error as applied to direct-current prepayment meters of 10-amperes rating or over, is to make the permissible error at 5 per cent. marked current $\pm$ 3·5 per cent. No error limit at this load is specified for ratings below 10-amperes marked current. In the case of alternating-current prepayment meters, the permissible error at 5 per cent. marked current and at unity power-factor becomes $\pm$ 3·0 per cent.; at 10 per cent. marked current and 0·5 power-factor (lag.), the permissible error is $\pm$ 3·5 per cent.

Although not explicitly stated, it may be inferred that these limits apply to the average error over a period of time. The operating conditions in a prepayment meter are such that the disturbing influences which affect the accuracy of the energy element may result in transitory errors in excess of the permissible limits. Notwithstanding this fact the error averaged over a sufficient period becomes relatively small. The important factor to bear in mind is that the value of the energy supplied to the consumer in return for one coin or a number of coins shall be within the limits laid down by the specification. It is immaterial to the consumer that, during the period between the insertion of a coin or coins and the opening of the switch thereafter, the meter may be fast

or slow outside the limits specified, provided that over this time interval the correct amount is delivered.

A coin-freed mechanism when well designed and carefully constructed, should exert little influence on the accuracy of the energy element by which it is controlled. It is difficult, however, to ensure that a coin-freed mechanism which, when geared mechanically to an energy element, shall exert no influence thereon at low loads, and consequently the error of the energy element is bound to vary to a certain extent according to the state of the coin-freed mechanism at any given instant. The extent of this influence will depend upon the number of coins prepaid, and also the price per kWh for which the mechanism is geared. During the period immediately prior to the tripping of the switch, the energy element may be called upon to exert some extra effort in order to overcome the additional friction. It is important not to confuse the error of the energy element with the error of the coin-freed mechanism. The energy element may be registering correctly and yet the amount delivered to the consumer may be incorrect as a result of premature or delayed tripping of the switch.

The accuracy of a two-part tariff prepayment meter is determined by the joint effect of three components (1) the energy element, (2) the fixed-charge element and (3) the coin-freed mechanism. Consideration has already been given to the energy element and the coin-freed mechanism and attention may now be devoted to the errors of the fixed-charge element. These errors may arise from two sources (1) the synchronous motor and (2) the variable-price mechanism. As a rule the synchronous motor is free from error, the speed being proportional to the frequency of the supply. If the frequency varies there will be a corresponding variation in the motor speed, but this cannot be regarded as a motor error. In any case, such a variation is of no practical importance because in normal circumstances in this country, such variations are cumulatively corrected and the average frequency over a 24-hour period shows no error.

Apart from the foregoing, two other factors may influence the motor speed; the first factor is excessive friction in the fixed-charge mechanism which, by imposing an undue load on the motor, may cause it to run slowly or stop altogether. Most motors have a high torque and run at 200 r.p.m. on a 50 c/s supply, consequently they develop considerable power. Any friction of such magnitude as to cause a reduction in motor speed should be immediately apparent on inspection.

The other factor results in the motor running overspeed, and is limited to one class of motor, namely, that which has an induction drive. The induction drive determines the direction of rotation of the rotor at the start. In this class a composite rotor is employed comprising a small permanent magnet and an aluminium cylinder. The synchronous speed for the permanent magnet is 200 r.p.m. and for the cylinder, is 600 r.p.m. The torque developed in the cylindrical rotor is a maximum at starting and diminishes rapidly as the speed rises. The torque developed in the permanent magnet is small at all speeds except at synchronous speed, that is at 200 r.p.m., when it reaches a sharp peak. At this speed the permanent magnet torque is in excess of the torque developed in the aluminium cylinder and overcomes any effort on the part of the cylinder to run at a higher speed. If however, the permanent magnet has weakened to such an extent that the torque which it develops ceases to exert the major influence, the cylinder takes control and the motor runs overspeed. Synchronous motors having rotors consisting of a permanent magnet only, cannot run overspeed.

Errors, if any, in the variable-price mechanism usually result in under-registration. As already described, this mechanism includes a device which periodically disconnects the motor from the terminal portion of the gear train for an interval which can be varied at will. When re-engagement of the gears takes place, there is the possibility that the pawl or other clutch device may fail to engage the first tooth, in which case under-registration will result.

Despite the possibilities of error referred to in the foregoing paragraphs, fixed-charge mechanisms are remarkably accurate and usually register the fixed charge without any error whatever. In such cases the overall accuracy of a two-part tariff prepayment meter is of a very high order. Assuming that 50 per cent. of the revenue collected consists of fixed charges which are registered without error and the remaining 50 per cent. consists of running charges, the cumulative error at the end of a quarter will be only half the average error due to the energy element. Thus, despite the increased tolerances permissible at 5 per cent. marked current in the case of prepayment meters, the actual errors in two-part tariff prepayment meters over a period are likely to be no greater and possibly less than those observed in credit meters.

CHAPTER VI

PREPAYMENT METERS: MODERN TYPES

6.1. Examples of Prepayment Meters. In the following pages, a short description is given of the salient features of prepayment meters of a variety of types. It is quite impossible to deal adequately in the space available with the very many prepayment meter types in use. A selection has been made however, with the object of illustrating some of the

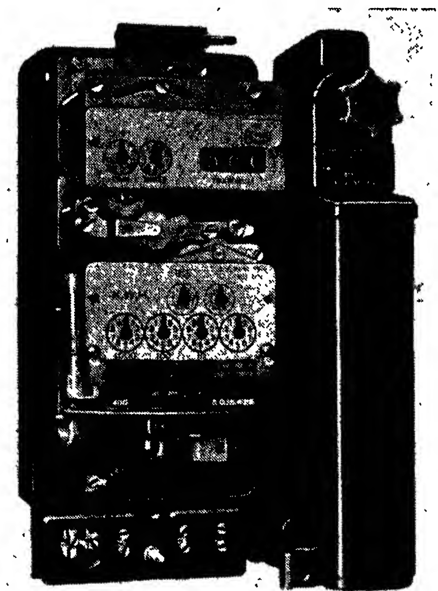


FIG. 60.—Ferranti single-rate prepayment meter, Type FLP.

outstanding differences which exist, as regards the constructional details of coin-freed mechanisms. The majority of these meters are in current production or have been manufactured until comparatively recent times. Amongst the exceptions are the step-rate and the direct-current two-part tariff prepayment meters which are included as a matter of interest. The step-rate was the predecessor of the two-part

tariff meter, and the direct-current two-part tariff meter is now of small importance because most domestic consumers in this country receive alternating-current supplies.

6.2. Ferranti Prepayment Meter, Single Rate. An illustration of a Ferranti single-phase prepayment meter, Type F.L.P. with the main cover removed is shown in Fig. 60. The main case on the left contains the energy element in the lower portion, and the coin-freed mechanism in the upper portion. The coin receiver is housed in a compartment separated from the main case and shown on the right with the coin-box below.

An illustration of the coin receiver with part of its casing cut away

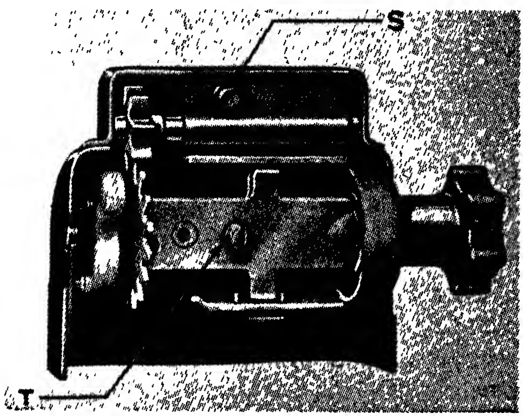


FIG. 61.—Coin receiver in Ferranti prepayment meter.

to expose the interior, is shown in Fig. 61. It is suitable for operation by shillings but can be converted easily for operation by pennies. It consists of two parallel plates separated by a space into which a coin can fall. The operating handle on the right projects outside the casing, and is secured to a half-cylindrical portion inside and partially encircling the coin receiver. The handle with the half-cylinder can be rotated freely around the receiver when no coin rests therein. A cam and a toothed wheel are secured to its left-hand extremity.

Immediately above the receiver is the coin entry also consisting of two parallel plates separated by little more than the thickness of a shilling and having a screw *S* so situated that a coin of correct diameter can just pass. The lower edge of the coin entry encloses a spindle having

a longitudinal slit, and a pinion on one extremity of the spindle gears with a toothed wheel on the coin receiver. A push rod passing through the side of the meter case rests against the surface of the cam and spring pressure on the rod maintains the receiver normally in a vertical position.

When a shilling is inserted it falls through the slit spindle in the lower edge of the coin entry and thence into the coin receiver where it projects upwards sufficiently to be engaged by one edge of the half-cylinder when the operating handle is turned in a clockwise direction. The coin thus forms a transmission piece between the handle and the receiver. Rotation of the receiver and the cam actuates the push rod and causes extension of the spring to which it is attached. The profile of the cam is such that after an angular movement of 150 deg. or thereabouts the spring completes the movement suddenly to 180 deg. independently of the handle. During this latter movement the switch is closed, if not closed already, and the coin falls out of the receiver into the coin-box. During the half-revolution of the coin receiver the slotted spindle geared to it makes one complete revolution, and this effectively prevents any attempt to withdraw the coin by the previous attachment of a strand of cotton.

To convert the receiver for operation by pennies instead of shillings the screw *S* in the coin entry is withdrawn and the screw *T* in the coin receiver is moved into the tapped hole seen on the left in the illustration. The price-change unit must also be exchanged at the same time. This latter can be seen in Fig. 60 immediately above the kWh register. Its removal can be effected by slackening off the two slotted nuts at its extremities, after which the unit can be lifted out.

The switch mechanism of the Ferranti prepayment meter is shown in Fig. 62. The switch, which is of the butt contact type as shown on the left at (*a*), consists of two massive copper contacts *1* and *2* arranged side by side, and bridged by a copper plate *3*. The contacts are fixed and the bridge piece is movable, the latter being attached to the free end of a horizontal toggle *4*. A second toggle *5*, arranged vertically, is attached by its free end to the hinge of the first toggle and a downward extension of the upper link can be forced into engagement with a latch *6*. In the illustration at (*b*), the toggle *5* is shown in the latched position with the switch closed, and at (*c*) is shown unlatched with the switch open. Closure of the switch is effected by movement of the toggle *5* communicated by the push rod, when an inserted coin establishes credit. Opening of the switch is effected by a trip pin *7* on the

eight-toothed star-wheel moving in an anti-clockwise direction and lifting the upper end of the latch lever *6*.

A novel feature in this switch, which is suitable for alternating current only, is the very short break; the bridge *3* is separated from the contacts *1* and *2* by a gap of 0·01 in. when the switch is open, the two gaps being in series. The current in the circuit is interrupted within 0·01 second, that is, during half a cycle on a 50 c/s supply. The actual break occupies 0·0002 second, this being followed by an arc which is a condition of intense air ionization. Owing to the very small gap between the contacts and the bridge-piece, the volume of ionized gas is correspondingly small and is rapidly cooled by the relatively large mass of copper in the contacts. This de-ionizes the gap as the current

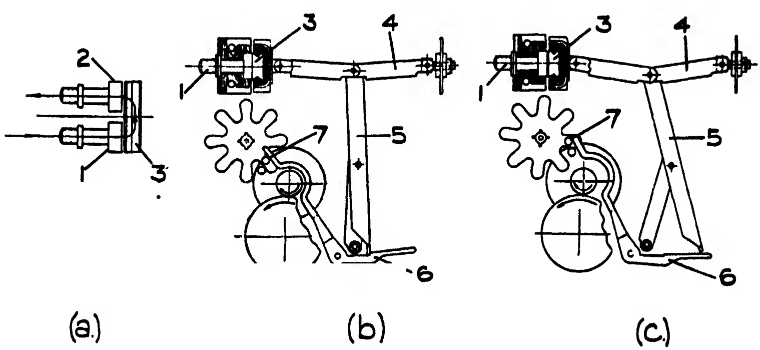


FIG. 62.—Switch mechanism in Ferranti prepayment meter.

wave passes through zero at the end of the first half-cycle and the current cannot re-establish itself during the succeeding half-cycle of the voltage wave. When the switch is closed, the pressure on the contacts amounts to sixty pounds per square inch, but owing to the double toggle device, the mechanical loading on the tripping system is very low and a very slight effort will suffice to open the switch.

6.3. Aron Prepayment Meter, Single Rate. The Aron single-phase prepayment meter, Type eP, in a cast metal case and adapted to a single rate tariff, is shown in Fig. 63 with the main cover and coin-box removed. The energy element occupies the left half of the case and the coin-freed mechanism the right half. The coin entry is to the right of the mechanism with the operating handle immediately below. The external operating handle is attached to the cover and has a slotted member inside which engages with the cross-pin forming the coupling

to the coin receiver. The mechanism is operable either by penny, sixpence or shilling coins and is easily convertible from one to another. A maximum of twelve coins can be prepaid at any time and the coin register indicates up to 999 coins inserted before repeating. The price per kWh can be varied by means of the price-change gear unit shown at *e*; this consists of two plates carrying a small train of wheels, the first of which gears with a wheel in the energy register, and the last, shown at *D*, with a wheel *E* in the coin-freed mechanism. A hook-shaped extension on one plate engages with the energy register and

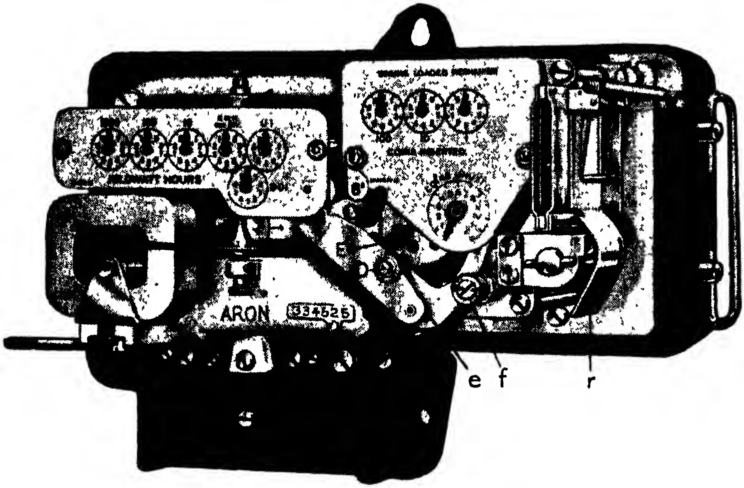


FIG. 63.—Aron single-rate prepayment meter. Type eP.

ensures correct meshing of the first wheel. A sector-shaped extension on the other extremity of the plate slides under a knurled nut *f* which can be locked when the wheels *D* and *E* are correctly meshed.

A skeleton view of the mechanism is shown in Fig. 64. The coin receiver consists of a cylindrical member having a vertical slot *1* into which the coin falls when inserted by the consumer; the edge of the coin rests on a screw *k* passing at right-angles through the slot. The position occupied by the screw in the illustration is suitable for shilling coins, but another position is available for the screw if it is desired to convert to operation by a sixpenny-piece. For penny operation, the screw is removed entirely. A mutilated sleeve *2*, partially surrounds the slotted cylinder and the sleeve can be rotated freely when the operating

handle, which engages with the cross-pin *3*, is turned. When a coin rests in the slot and the operating handle is turned in a clockwise direction (as seen by the operator), the lip *2A* of the sleeve engages the coin and turns the cylinder together with the toothed wheel *4* attached to its

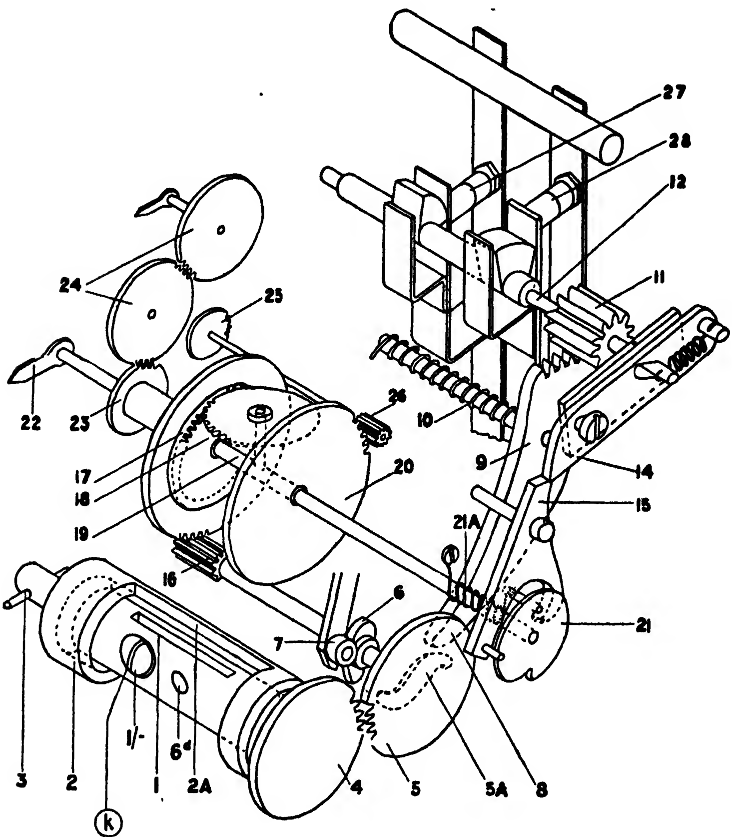


Fig. 64.—Arrangement of mechanism in Aron prepayment meter.

extremity. The wheel *5* together with the cam *5A*, the double-ended cam *6* and the pinion *16*, are all driven by the wheel *4*. A lever carrying a roller *7* on its extremity bears against the double-throw cam *6*, and when the coin receiver has turned rather more than 90 deg., the roller will have risen over the crest of the cam and will suddenly ride down the inclined face, causing the coin receiver to complete a turn of 180 deg.

from its initial position. This sudden movement ejects the coin into the coin box and the pinion *16*, driving through the sun wheel *17* and planet wheel *18*, turns the main shaft *19* and advances the index of the credit indicator *22*. Rotation of the sun wheel *17* also advances the coin register through the wheels *23* and *24*.

The first coin to establish a credit actuates simultaneously the switch-closing and latching mechanism in the following manner. Rotation of the toothed wheel *5* also rotates the cam *5A*, one end of which strikes the tail of the switch quadrant-lever *8*. This lever, which is pivoted at *9*, is deflected by the cam *5A* against the tension of the spring *10*, and the pinion *11* mounted on the switch-operating shaft *12*

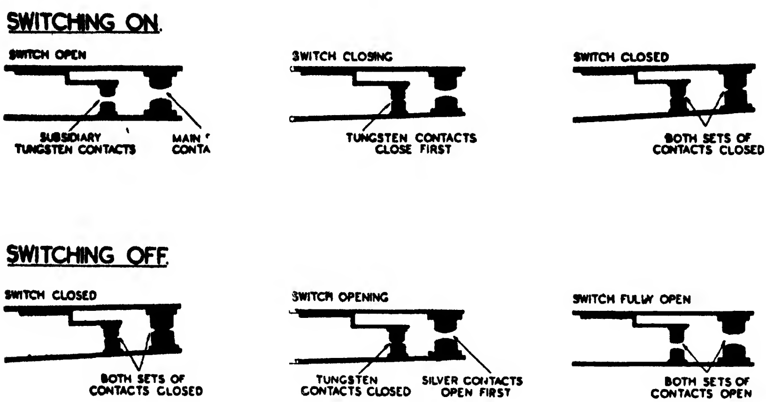


FIG. 65.—Details cf switch mechanism in Aron prepayment meter.

is turned in the direction to close the switch contacts *27* and *28*. The switch-arm click *14* mounted on the same shaft is turned from a vertical (open) position to a horizontal (closed) position, where it is held by the latch *15*.

Opening of the switch is effected by the operation of the energy element acting through the wheel *25* and pinion *26* driving on to the sun wheel *20*, thus turring the planet wheel *18* and main shaft *19* in the debit direction. This reverses the movement of the credit indicator and also rotates the cam *21* until credit is exhausted. At this moment a pin on the inside face of the cam *21* deflects the latch *15* sufficiently to release the switch-arm click *14*, whereupon the spring *10* acting on the switch quadrant-lever *8*, rotates the pinion *11* and shaft *12*, thus opening the switch contacts *27* and *28*.

A novel feature in the switch is in the provision of two pairs of contacts and these are illustrated in Fig. 65. The main contacts have surfaces of pure silver and carry 95 per cent. of the total current. The subsidiary contacts are of tungsten or tungsten alloy and carry the remaining 5 per cent. of the current; the make and break duty is carried out by the subsidiary contacts which are connected in parallel with the silver contacts. They are so arranged that they make before, and break after the silver contacts during switching operations. This relieves the silver contacts of the wear and tear due to arcing, and as tungsten contacts do not weld together and maintain an arc, the effective life of the switch is increased.

6.4. Smith Prepayment Meter, Single-Rate. The Smith prepayment meter, Type AP., manufactured by Smith Meters Ltd., and shown in Fig. 66 is an example of a meter in which a unit price-change device is combined with the coin receiver. The coin receiver, which is removable, is housed in a cylindrical cavity in the right-hand upper corner of the case, and is shown below the meter in the illustration. The coin entry to the receiver consists of a radial slit in the circular plate, and when the receiver is replaced in the cavity one of the serrations in the edge of the plate will be engaged by a locating peg projecting from the lip of the cavity. The retaining ring alongside the coin receiver is then placed over the serrations, and is locked in position by turning clockwise through 90 deg. or thereabouts the small lever seen between the cavity and the credit indicator. When the coin-box is inserted and the hinged cover is closed and locked, it is not possible to alter the position of the coin receiver in the cavity.

The meter is constructed for operation by shillings or sixpences, and is easily convertible from one to the other. The conversion is effected by removing the coin receiver from its cavity and altering the position of a metal block relative to the coin entry. The latter is of sufficient length to accept a shilling, but when the block is moved across the entry, the length is restricted to the diameter of a sixpence.

An engraved scale shows the number of units per coin corresponding to various positions of the circular plate, and the figure adjacent to the locating peg indicates the particular value for which the mechanism is set at any time. Projecting behind the receiver is a lever, the extremity of which swings in an arc around the circumference of the toothed wheel seen in the rear of the cavity. To prepay a coin, the handle of the receiver is turned as far as it will go in a clockwise direction and this action will reveal the coin slot. On inserting the appropriate coin

the extremity of the lever will be moved radially towards the centre of the toothed wheel and will engage one of the slots between the teeth. If the handle be now turned in an anti-clockwise direction the coin receiver and the coin therein will be rotated, carrying with it the toothed wheel. A slot in the bottom of the cavity communicates with the coin-box and when the coin in the receiver comes opposite the slot,

FIG. 66.—Smith single-rate prepayment meter. Type AP.

it is ejected by spring pressure into the coin-box. Simultaneously the lever which couples the coin receiver to the toothed wheel is disengaged and the handle may then be turned back to prepay another coin.

The toothed wheel when rotated advances the credit side of a differential gear and also the credit indicator. It will be seen that the amount of angular movement communicated to the toothed wheel will be determined by the angular distance traversed by the coin between

insertion into, and ejection from, the coin receiver, and as this distance is adjustable at will it serves as a means to adjust the number of units delivered for each coin inserted. Because the adjustment is made on the coin-driven side of the differential, the credit indicator is scaled in terms of "unused units".

The range of price adjustment which can be obtained by means of this mechanism varies from 1·0 unit per coin to 4·7 units per coin, in steps of 0·1 unit. A small gear-change device is incorporated in the mechanism which enables the values to be increased four-fold; this device is accessible by removing the cover of the meter. The credit indicator has two scales designated "*A*" rate and "*B*" rate respectively, and corresponding to the foregoing price ranges. Full scale at the "*A*" rate corresponds to 22 units unused and at the "*B*" rate, 88 units unused. A separate indicator associated with the gear-change device shows which of the two rates is in operation at any time.

Since the cover of the coin receiver is scaled in terms of "units per coin", the corresponding price in "pence per kWh" will depend upon the value of the operative coin. If the operative coin is one shilling the possible variations in price per kWh will range between 12 pence and 2·55 pence at the "*A*" rate, and between 3 pence and 0·638 pence at the "*B*" rate. If the operative coin is a sixpence these values will be halved. The changes in the values of "units per coin" as engraved on the cover of the coin receiver occur, as already stated, in equal steps of 0·1 unit, but the reciprocals of these values, that is the corresponding "pence per kWh" are not in equal steps. The variations which occur in practice between the prices per kWh are usually in steps of one halfpenny for the high rates and one farthing or one-eighth of a penny for the low rates. Because some of the usual prices per kWh cannot be obtained exactly, it is customary to set the price to the next higher value on the scale, and at the end of each period when the meter-reader collects the money from the coin-box, the excess amount which has been prepaid by the consumer is refunded.

6.5. Chamberlain and Hookham Prepayment Meter, Single Rate. A Chamberlain and Hookham single-rate prepayment meter, Type JPM with cover removed, is shown in Fig. 67. It comprises an energy element on the left combined with a dual-coin prepayment mechanism above, and with the coin-box below the mechanism on the right. It is arranged for operation by pennies and shillings, and the coin register shows the value of the inserted coins to a total of £20, reading in pounds, shillings and pence. The credit indicator shows the value of

the coins unused to a total value of 120 pence. The coin-freed mechanism is built as a complete unit and can be removed by disconnecting two wires and slacking off three screws, after which the mechanism is slid to the left and withdrawn. The mechanical connection between the coin-freed mechanism and the energy register is effected through the meshing of two gear wheels, one in the register and the other in the mechanism, and seen immediately below the credit indicator.

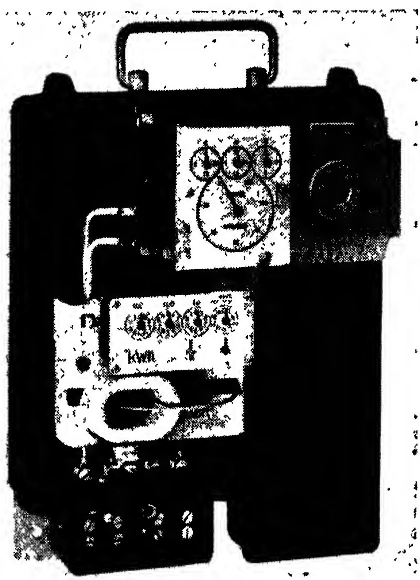


FIG. 67.—Chamberlain & Hookham single-rate prepayment meter. Type JPM.

Correct meshing of these wheels is ensured automatically, and a strap joining the register to the mechanism prevents variation in depth of mesh due to springing. The operating handle which is attached to the meter-cover has two pins which engage in two holes seen in the clutch to the right of the mechanism.

An illustration of the coin-freed mechanism from the rear, showing the switch details, appears in Fig. 68. A mercury switch is fitted consisting of a tube of insulating material having two contacts so arranged as to be bridged by mercury when the tube is horizontal, but electrically separated when the tube is tilted. Flexible insulated leads connect the

switch contacts with a terminal block on the backplate. The switch is supported on a pivoted lever and an arm which is vertical when the switch is closed is connected to this lever. A steel pallet attached to the upper end of the switch arm engages, in the closed position, with a similar steel pallet on the end of a switch-retaining lever occupying a horizontal position. The switch-retaining lever is pivoted at the end remote from the engaging pallet and has a vertical arm which lies in the path of the switch trip-pin forming part of a crank mounted on the rear end of the differential arbor. As the index of the credit indicator

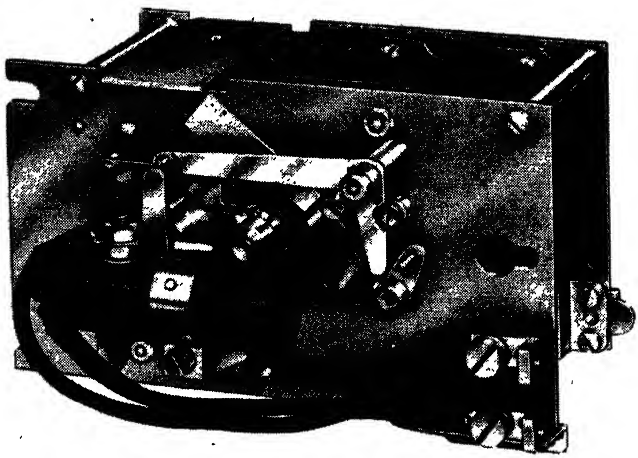


FIG. 68.—Coin-freed mechanism in Chamberlain & Hookham prepayment meter.

approaches its zero position the switch trip-pin engages the tail of the switch retaining lever, causing the horizontal arm to lift slightly and release the vertical switch arm. The switch then falls by gravity to the open position; the passage of a coin through the mechanism reverses these actions and lifts the switch into the closed position where it remains until credit is exhausted.

The coin receiver is arranged for operation by pennies and shillings. When a coin is inserted through the coin entry it falls by gravity into a cylinder arranged horizontally and slotted along its axis. The coin comes to rest on a retractable support, with part of its diameter projecting upwards, out of the slot. A sleeve surrounding the forward end

of the cylinder has a short pin projecting inwardly into the longitudinal slot in the cylinder. Two grooves are cut in the circumference of the cylinder, which latter can be turned by the operating handle when the pin in the sleeve is opposite either of the grooves. In all other positions the pin prevents rotation of the cylinder.

When a coin is resting in the cylinder and the operating handle is turned from its initial position, the sleeve slides along the cylinder until arrested by pressing against the edge of the coin. If the coin is of correct diameter, the pin in the sleeve will then be opposite one of the grooves and further movement of the handle will rotate the cylinder together with the coin. The latter acts as a transmission piece between the cylinder and a cam, against which rests a spring-controlled lever. Rotation of the cam extends the spring, and when the cam has turned through an angle of 90 deg. or thereabouts, it reaches a dead-centre. Further movement beyond the dead-centre allows the spring to contract and the cam suddenly completes a turn of 180 deg. independently of the operating handle. Simultaneously the coin is ejected from the cylinder into the coin-box, the credit mechanism is advanced, the switch closing mechanism is actuated, and the cylinder reverts to its normal position ready to receive another coin.

The amount of advance of the credit indicator and the coin register is determined by a gear selector actuated from the sleeve. A long pin projecting outwardly from the sleeve engages with a pair of sliding pinions, one having twelve teeth and the other, one tooth only. One or other of these pinions can drive a third pinion geared to the differential, the twelve-tooth pinion engaging when a shilling is passed through the coin receiver and the one-tooth pinion when a penny is passed. Thus the advance of the differential in the credit direction will be in proportion to the value of the operative coin. If a coin of incorrect diameter is inserted, the sleeve will not permit rotation of the cylinder and the coin must be ejected. This is accomplished by pressing a button projecting through the meter-casing, which action retracts the support under the coin receiver; the coin then falls out of the slot into the coin box below. In some meters provision can be made for the rejected coin to fall into a channel through which it is returned to the consumer.

Alteration in the price per kWh is effected by means of a price compound consisting of a small train of wheels mounted in a removable bracket and joining up the energy register with the differential. The gear ratio of this train can be varied over wide limits and permits the price per kWh to be adjusted exactly to any desired figure. The price

compound is latched in position by a hinged lever shown in Fig. 67 on the front of the mechanism in the bottom left-hand corner. It may also be seen in Fig. 68 in the right-hand bottom corner of the front plate. Removal of the compound is effected instantly by swinging the latch in a clockwise direction and sliding the bracket to the left; when the bracket is removed, a light spring engages with the teeth of the sun wheel on the differential and prevents the return of the credit indicator to zero, should there be any coins unused when the alteration is made. Replacement of the compound disengages the spring simultaneously

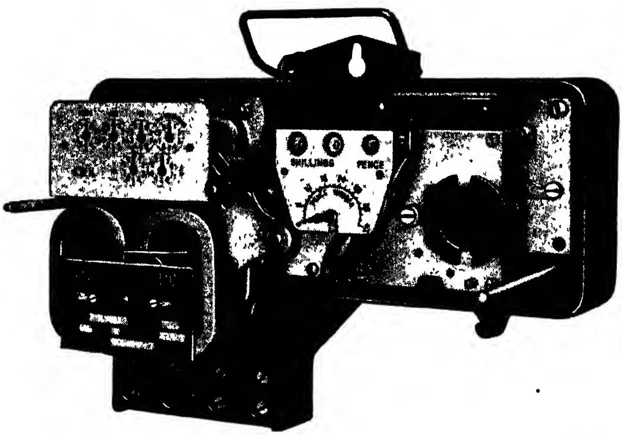


FIG. 69.—Metropolitan-Vickers dual-coin prepayment meter. Type NEI.

with the re-engagement of the gears. The compound is automatically located in the correct position for meshing with the register and the differential and no adjustment of the gearing is necessary.

6.6. Metropolitan-Vickers Prepayment Meter, Single Rate. The meter shown in Fig. 69 is a Metropolitan-Vickers single-rate dual-coin prepayment meter, Type NEI, with cover removed. It is housed in a bakelite case and is constructed for operation by pennies and shillings. The energy element on the left is coupled to the prepayment mechanism on the right, through a price-change gear unit. This latter is self-locating and is secured in position by means of a knurled nut adjacent to the credit indicator. The coin register indicates the total value of coins inserted up to one hundred shillings before repeating. The credit indicator indicates the amount prepaid up to a maximum value of 42 pence.

The coin receiver which is attached to the inside of the cover of the meter (not shown in illustration), consists of a rotatable frame contained within a cylindrical body, the frame being capable of turning freely through half a revolution by means of the operating handle which projects outside the cover. Two concentric shafts fitted with dog clutches project from the rear of the body, and the mating parts with which they are coupled when the cover is in position on the meter can be seen in the illustration.

When no coin is in the receiver the frame within the cylindrical body can be rotated independently of the concentric shafts, but when a penny is inserted through the coin entry a spring-controlled finger-piece is deflected into a position where the frame is coupled to the

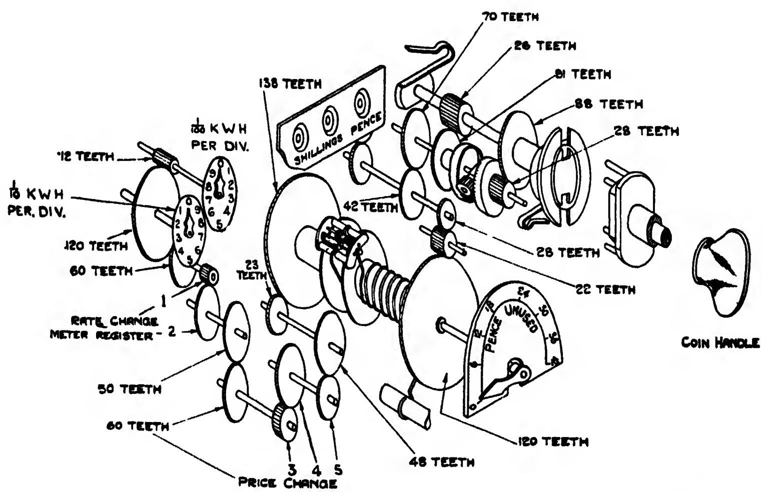


FIG. 70.—Arrangement of gearing in Metropolitan-Vickers prepayment meter.

innermost shaft. Rotation of the operating handle under this condition will also rotate the innermost shaft. When a shilling is inserted, the finger-piece already referred to couples the frame to the innermost shaft as before and a second finger-piece is deflected into a position where the outermost shaft is also coupled to the frame. Rotation of the operating handle under this condition will rotate both shafts, together with their mating parts (the coupling plates) on the prepayment mechanism; after turning the operating handle through 180 deg., the coin is ejected from the receiver into the coin-box located immediately below.

The arrangement of the gearing in the Metropolitan-Vickers dual-coin prepayment mechanism is shown diagrammatically in Fig. 70. The operating handle together with the mating parts between the coin receiver and the prepayment mechanism are shown to the right of the diagram. Two coupling plates, an inner and an outer, on the front of the mechanism, can transmit motion from the coin receiver to a differential gear. When a penny is passed into the receiver and the operating handle is turned the innermost shaft drives the inner coupling plate which is secured to a shaft carrying a 26-tooth pinion. This pinion engages a wheel having 91 teeth secured to one of the sun wheels of a differential. When a shilling is passed through the receiver both coupling plates are driven and in addition to the 26-tooth pinion being turned an 88-tooth wheel secured to the outer coupling plate and running freely on the shaft is also turned. This latter wheel drives a 28-tooth pinion secured to the other sun wheel of the differential. Thus actuation of the mechanism by one penny drives one side of the differential only but actuation by one shilling drives both sides and the angle through which the main shaft of the differential is turned in the latter case is twelve times as great as in the former.

The motion communicated to the main shaft of the differential referred to above is passed on to a second differential through wheels having 70, 42, 28, 22 and 120 teeth respectively. The 120-tooth wheel is secured to the coin-driven sun wheel of the differential. The energy element drives through a train of wheels on to a 138-tooth wheel secured to the meter-driven sun wheel of the differential. The main shaft of the differential carries at its forward extremity, the index of the credit indicator, the dial for which may be seen in Figs. 69 and 70.

6.7. Chamberlain and Hookham Prepayment Meter, Step-Rate. Step-rate meters, both direct-current and alternating-current types, have been made by Chamberlain and Hookham Ltd., but are no longer in production. The one illustrated in Fig. 71 is a single-phase meter arranged for operation by shilling coins. The dial plate of the coin-freed mechanism has three sets of indices; the upper index shows the number of coins unused and registers a total of four shillings. This index shows only the proportion of the value of the inserted coin which is credited towards the supply of energy and does not include that portion which is credited to standing charge. After the whole of the standing charge has been paid off in any quarter the whole of each coin subsequently inserted is credited to the supply of energy.

The middle set of indices shows the total number of coins inserted

into the meter; the lower index shows the total number of kWh to be used at the normal (high) price before the lower-priced units become available in any quarter. This in effect covers the standing charge, which is equivalent to the number of units at the higher price multiplied by the difference in price between high- and low-price units. The lower index is set by the meter-reader each quarter when the coin collection is made. To set the index the coin drawer is removed and it is then possible to uncover a keyhole on the right of the index. On inserting a

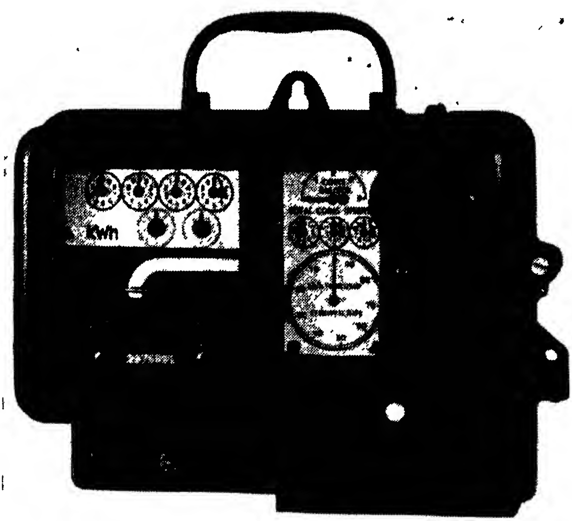


FIG. 71.—Chamberlain & Hookham step-rate prepayment meter.

key, the index may then be set in the desired position. If in any quarter the whole of the higher-priced units have not been used, the outstanding quantity can be added to the quantity due to be used in the succeeding quarter.

The arrangement of the gearing in the coin-freed mechanism of the Chamberlain and Hookham step-rate prepayment meter is shown in Fig. 72 from which it will be noted that the mechanism incorporates two interconnected differential gears. The operation of the mechanism is as follows:—At the commencement of the quarter the standing-charge index is set by an official of the supply authority to the number of kWh to be used at the normal rate. This is accomplished by inserting

a key through a hole in the meter-cover and turning an arbor having a squared end. A pinion on this arbor engages a wheel attached to a friction sleeve mounted on a second arbor and carrying the standing-charge index; a ratchet and pawl (not shown) prevents any movement of the sleeve from being communicated to the other parts of the mechanism.

When a coin is inserted in the coin receiver and the operating handle is turned the two wheels *C* and *D* are advanced in the direction shown

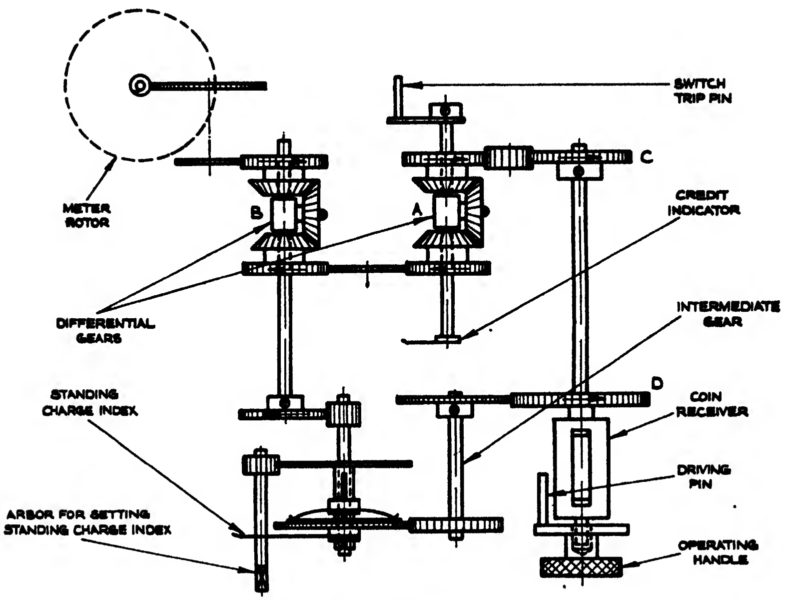


FIG. 72.—Arrangement of gearing in Chamberlain & Hookham step-rate prepayment meter.

by the arrows thereon. Wheel *C* drives on to one of the sun wheels of the differential gear *A*, and causes the switch trip-pin to move away from the tripping position, the switch closing simultaneously. Wheel *D* drives through intermediate gearing to the standing charge mechanism and moves the standing-charge index towards the zero position. It also drives the arbor carrying the planet wheel of differential *B*, and thence through one of the sun wheels on to a sun wheel of differential *A*, the direction of motion being indicated by arrows. Thus, the acceptance of a coin by the mechanism cancels a portion of the standing charge

and at the same time renders available to the consumer a limited amount of electrical energy.

The arbor on which differential *B* is mounted is stationary at all times, except when a coin is being passed through the mechanism. Consumption of energy for which prepayment has been made results in motion being transferred from the meter rotor through differential

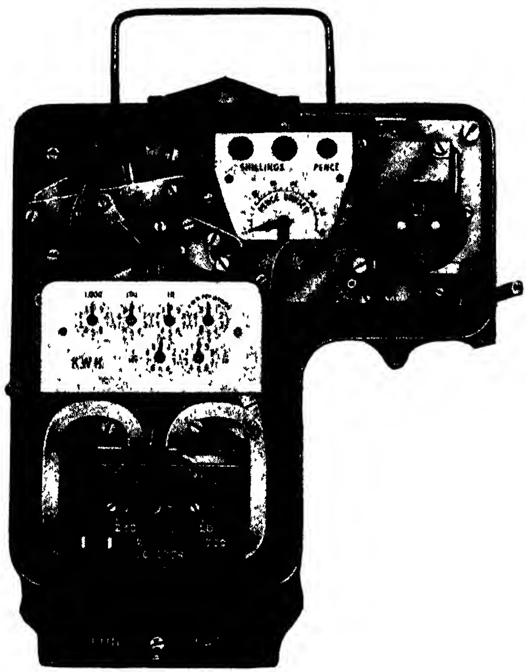


FIG. 73.—Metropolitan-Vickers load-rate prepayment meter. Type NE.

B in the direction as indicated by arrows, to the lower sun wheel of differential *A*. This runs down the credit indicator or coins unused index, and the switch trip-pin moves towards the zero position, on reaching which, the switch opens.

When a sufficient number of coins have been inserted, each of which has cancelled a portion of the standing charge, and the whole of this latter has been paid off, the standing charge index will have reached the zero position: thereafter, the passage of coins through the mechanism

will not transmit any movement from the coin receiver to differential *B*. The wheel *D* and the intermediate gear will still be driven each time a coin is passed through, but a stop-pin arrests the index, and slip will now occur between the driving-wheel and the arbor carrying the standing charge index, with the result that the arbor will remain stationary. The effect of this slip is to prevent any motion being communicated from the coin receiver shaft to differential *A*, except through the wheel *C*. The advance shown on the credit indicator will now be greater, per coin inserted, and consequently the cost of each kWh

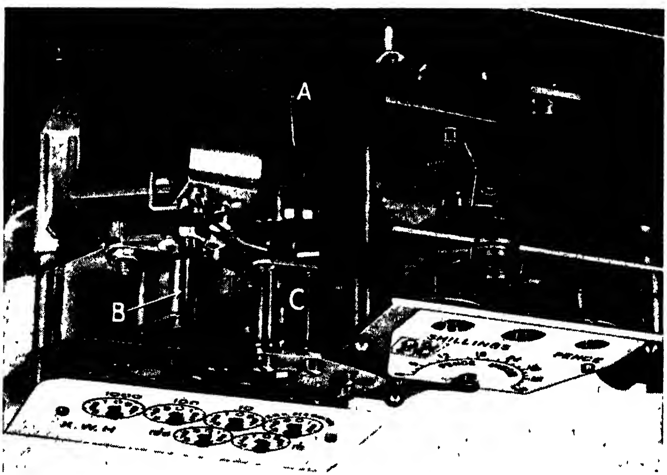


FIG. 74.—Coin-freed mechanism in Metropolitan-Vickers load-rate prepayment meter.

rendered available will be reduced until such time as the standing charge index is reset.

6.8. Metropolitan-Vickers Prepayment Meter, Load-Rate. A dual-coin load-rate prepayment meter, Type NE, manufactured by Metropolitan-Vickers Electrical Co. Ltd., is shown in Fig. 73 with cover removed. The coin-freed mechanism is in the upper right-hand corner and the electro-magnetic changeover device in the upper left-hand corner. A close-up view of the coin-freed mechanism is shown in Fig. 74. The armature of the electromagnet *A* can be adjusted so as to effect the changeover from primary to secondary rate when the load exceeds 1·7 amperes on a 5-ampere or 10-ampere meter, corresponding

to 400 watts at 240 volts. On a 20-ampere meter the point at which the changeover takes place is 2·5 amperes, corresponding to 600 watts at 240 volts. Special meters can be made with a higher, but not a lower, changeover point.

The relative disposition of the parts of the coin-freed mechanism in this load-rate meter are, in general, as shown in Fig. 55, but, being a dual-coin meter the coin receiver is of different construction; some details of a Metropolitan-Vickers dual-coin prepayment meter are given on page 183. The primary rate is determined by a price-change gear unit occupying the position of the intermediate gear in Fig. 55 and the ratio of primary to secondary rate by a ratio gear-change unit between the intermediate gear and the kWh register. In Fig. 74 the price-change gear unit is shown at C and the ratio gear-change unit at B. Both units can be easily exchanged if it is desired to alter the primary rate or the ratio of primary to secondary rate. The following table gives the range of prices per kWh which can be obtained with standard gear units:—

TABLE 5

Range of Prices per kWh obtainable with Standard Gear Units in Metropolitan-Vickers Load-Rate Meter.

Ratio of Primary Rate to Secondary Rate.	Primary Rate per kWh in Farthing Steps.		Corresponding Secondary Rate per kWh.	
	Min.	Max.	Min.	Max.
6 to 1	3·0 pence	12 pence	0·5 pence	2 pence
5 to 1	2·5 „	10 „	0·5 „	2 „
4 to 1	2·0 „	8 „	0·5 „	2 „
3 to 1	1·5 „	12 „	0·5 „	4 „
12 to 5	1·2 „	9·6 „	0·5 „	4 „

6.9. Smith Prepayment Meter, Triple-Coin, Two-Part Tariff. The triple-coin, two-part tariff prepayment meter, Type A.P.F., manufactured by Smith Meters Ltd., is illustrated in Fig. 75. It is an example of one in which provision is made for a combination of all the adjustable devices which may be desired in a two-part tariff prepayment meter. It combines

in one instrument the facility for operation by the consumer with any one of three optional coins, means for adjustment by the supply authority of the weekly fixed charge, and means for adjustment of the price per kWh over a wide range.

The energy element is located in the lower left-hand portion of the bakelite case; immediately above is the adjustable mechanism for

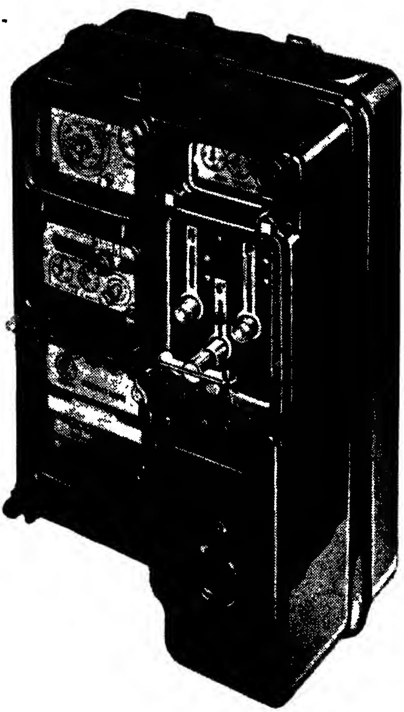


FIG. 75.—Smith triple-coin two-part tariff prepayment meter. Type APF.

varying the price per kWh together with the credit indicator which shows this quantity in terms of unused units. In the top left-hand corner of the case is located the adjustable fixed-charge mechanism, alongside which is visible in the same window opening an index showing the arrears of fixed charge, if any. In the top right-hand corner of the case may be seen the coin register which can read up to twenty pounds before repeating. Below the coin register are three separate coin entries

together with one operating handle which actuates the three coin receivers simultaneously.

The coin box is located below the coin entries and alongside the energy element; a stem passing through the middle of the coin box and projecting beyond its front face can accommodate the hasp of a padlock to prevent withdrawal. A window, hinged at the top of the case, permits access for the purpose of adjustment to the fixed-charge and price-change mechanisms when the coin-box is withdrawn. A horizontal bar having a cam action and a lever extension on the right is located below the window. Actuation of the bar by unauthorized persons, for the purpose of opening the window, is prevented by a projection from the face of the coin-box, which lies over the lever extension when the coin box is in its normal position.

The three coin entries are arranged to take penny, sixpence and shilling coins and the operating handle when turned can rotate all three coin receivers. Each coin is gauged at entry and an oversize coin will not pass. An obstruction in the penny and shilling entries prevents the insertion of undersize coins, but if a coin smaller than a sixpence is inserted in the sixpenny slot, it falls through the receiver into the coin-box. If a coin is inserted in the correct entry and the operating handle is turned, the coin acts as a transmission piece and advances the credit mechanism by an appropriate amount. If two or three coins are inserted into their correct receivers and the operating handle is turned, the credit mechanism will be advanced by an amount corresponding to the total value of the coins. Two differential gears are employed to summate the movements of the three coin receivers.

The credit indicator has two pointers showing unused units and when direct reading, will indicate the amount prepaid up to 100 kWh. On reaching this value a lever is actuated which moves a shutter over the coin entries and prevents the insertion of additional coins until the credit has been reduced. Combined with the credit-indicator unit is a mechanism for enabling the price per kWh to be conveniently changed. This consists of a cone of thirty-seven gear wheels mounted on an arbor, the diameter of the wheels increasing progressively from small at one end to large at the other. A second arbor consisting of an elongated pinion lies parallel to the first, and mounted thereon is a selector frame carrying a small train of wheels which can slide along the pinion and engage any selected one of the 37 wheels in the cone. A gear-change device which can be operated by turning a screw-head permits the normal unit prices and credit values to be multiplied or

divided by four. Thus, the credit indicator will show a maximum credit value of 400, 100, or 25 kWh according to which gear ratio is selected and the prices per kWh can be varied in 108 steps as follows:

(*a*) 1s. 4d. to 1s. per kWh in steps of 1d. and thence to 4d. in steps of $\frac{1}{4}$d. per kWh.

(*b*) 4d. to 3d. per kWh in steps of $\frac{1}{4}$d., and thence to 1d. in steps of $\frac{1}{16}$d. per kWh.

(*c*) 1d. to $\frac{3}{4}$d. per kWh in steps of $\frac{1}{16}$d., and thence to $\frac{1}{4}$d. in steps of $\frac{1}{64}$d. per kWh.

The fixed charge element in the Smith prepayment meter shown in the left-hand top corner of Fig. 75 consists of a train of gears driven by a small synchronous motor connected across the supply mains and running continuously. The arrangement of the gearing is shown in Fig. 76. The dial of the fixed charge element has two scales arranged concentrically, the outer scale printed in red reading from 6d. to 9s. 6d. per week in steps of 1$\frac{1}{2}$d., and the inner scale printed in black reading from 2d. to 3s. 2d. per week in steps of $\frac{1}{2}$d. The index finger which is hinged on the end of its supporting arbor can be lifted and turned over to occupy a position 180 deg. from its original position; the tip of the index is coloured red on one side and black on the other, the colour indicating which scale is to be observed. The action of reversing the position of the index transfers the synchronous motor drive from one worm to another and causes the rate of registration to be three times as great on the outer scale as compared with the inner scale. The setting of the weekly charge is accomplished by turning the screw-head marked "set" in the direction of the arrow, which action rotates the scales relative to the index.

If the consumer fails to maintain a credit balance, the "unused units" indices reach zero and then come to a standstill; the switch opens at this point and interrupts the supply, but the synchronous motor continues to drive the mechanism in the debit direction and the arrears in the weekly payments are indicated in shillings on the arrears dial to the right of the fixed charge index. The maximum amount of arrears which can accumulate is thirty shillings.

It is customary in most makes of meter to arrange that the switch cannot reclose until all arrears have been paid off. This practice can also be followed in the Smith meter, but a device is incorporated whereby, at the option of the supply authority, the switch will reclose after the

insertion of a few pence, notwithstanding the fact that some arrears remain unpaid. If this device is utilized, the rate of collection of the fixed charge is doubled during the period in which arrears remain. The

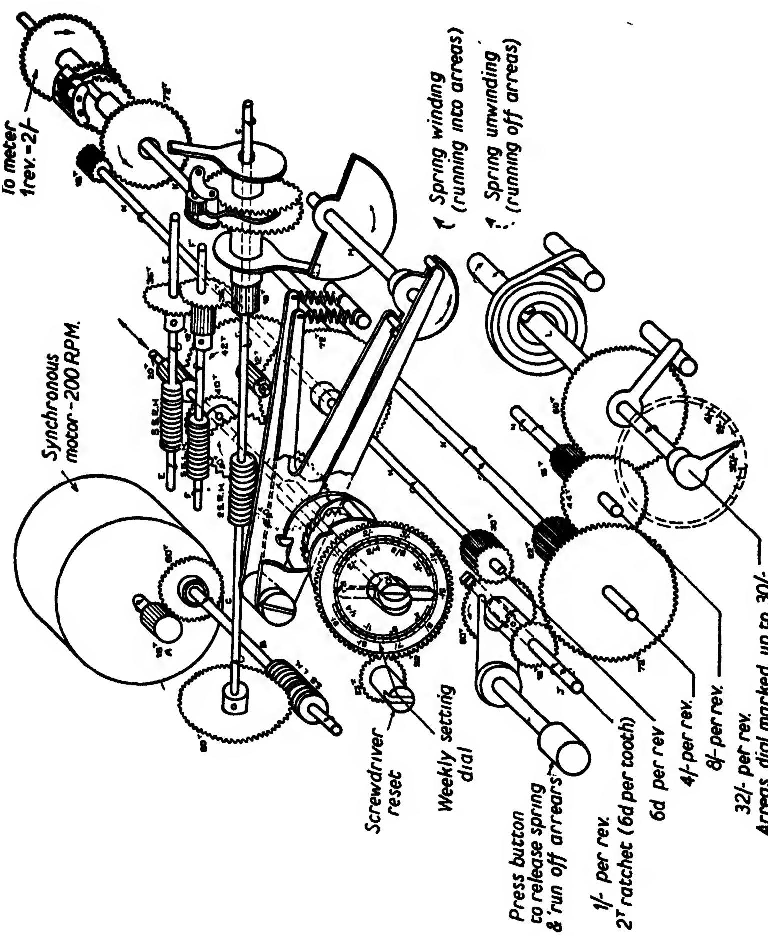


FIG. 76.—Arrangement of gearing in Smith prepayment meter.

selection of the method of collecting arrears is determined by the position of a lever which can be set by the meter-reader. Immediately below the arrears dial shown in Fig. 75 are two holes, the upper one being larger than the lower. To the left of these holes is a button which forms the pivot for a lever carrying a pin at its extremity, which

pin can engage with either of the holes if the button is depressed and turned. If the pin is caused to engage in the lower hole, the arrears must be completely paid off before the supply can be restored, but if the pin engages in the upper and larger hole, the arrears can be paid off by degrees.

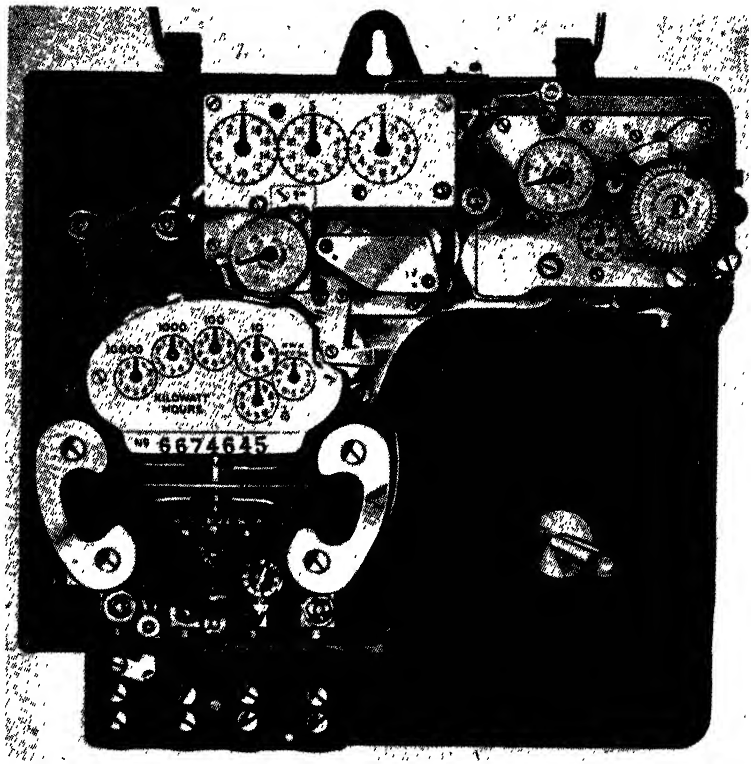


FIG. 77.—Sangamo triple-coin two-part tariff prepayment meter.

6.10. Sangamo Prepayment Meter, Triple-Coin, Two-Part Tariff. A triple-coin, two-part tariff prepayment meter manufactured by Sangamo Weston Ltd., is shown with cover and coin box removed in Fig. 77. It comprises an energy element in the lower half of the case, with the coin-feed mechanism in the upper half. It is operable by penny, sixpenny and shilling coins, and the coin box occupies the space on the right of the energy element. The fixed-charge element consists

of a detachable unit located on the front of the coin-freed mechanism at the extreme right. A coin register reading in pounds, shillings and pence, to a total value of twenty pounds, may be seen above the energy element. A credit indicator, consisting of a revolving index and scale, is located on the left below the coin register, the indication being in terms of "Units unused." As the differential mechanism is of the

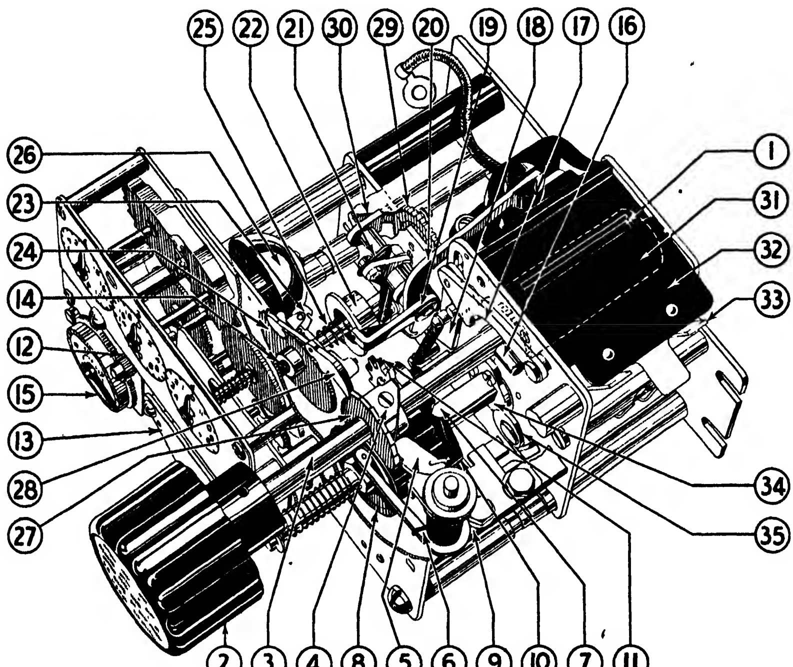


FIG. 78.—Arrangement of gearing in Sangamo prepayment meter.

"screw and nut" variety, the scale is advanced when credit is established and the index follows in the same direction when consumption or lapse of time reduces the credit. A price-change gear unit for varying the price per kWh is mounted to the right of the credit indicator, and is secured in position by two screws. If the gear unit is exchanged for one of a different value, it is automatically located in the correct position by dowel pins and no adjustment to the depth of gearing is necessary.

The coin-freed mechanism is shown in diagram form in Fig. 78. The operating handle (2) which is attached to the meter cover, engages with a cross-pin on the shaft (3) carrying a caliper cam (4). When the operating handle is turned, the caliper cam advances a cam lever (5) together with a selector lever (6) and selector shaft (7). The distance moved by the selector shaft depends upon the diameter of the coin which has been passed through the coin slot (1) into the coin receiver (31); the selector shaft carries a selector cam (8) and a mutilated pinion (10). Adjacent to the selector cam is a selector plate (9) having three slots in its edge. When a coin, penny, sixpence or shilling, as the case may be, has been passed into the coin receiver and the operating handle is turned the selector cam comes to rest opposite one of the slots in the selector plate. The operating shaft and the selector shaft are geared together, and further rotation of the operating handle causes the edge of the selector cam to enter one of the slots in the selector plate. Thereafter, until the operating handle has completed a revolution, the position of the mutilated pinion is in fixed relationship to a gear wheel (11) having twelve teeth, and mounted on a shaft which drives through appropriate gearing on to the credit side of a differential gear.

The mutilated pinion has three sections having one, six and twelve teeth respectively. When a shilling rests in the coin receiver and the operating handle is turned the twelve-toothed portion of the mutilated pinion will engage with the twelve-tooth gear wheel (11). A complete revolution of the operating handle will advance the latter also by one revolution; if the coin in the receiver is a sixpence or a penny, the six-toothed or one-toothed sections of the mutilated pinion will engage and will advance the twelve-tooth gear wheel by one half or one twelfth of a revolution respectively. Thus, the credit side of the differential and also the credit indicator will advance in proportion to the value of the coin which passes through the mechanism. On completion of this operation the selector cam is disengaged from the selector plate and flies back together with the mutilated pinion to its initial position. If no coin, or a coin having a diameter differing from that of a penny, sixpence or shilling is passed into the coin receiver, the mechanism cannot be operated because the position of the selector cam will not be opposite one of the slots in the selector plate, and consequently the edge of the cam cannot enter a slot. For the release of incorrect coins a white push-button is provided on the right-hand side of the meter which, when pressed, allows the coin to fall out of the receiver into the coin box. The incorrect coin is not registered on the coin register and may

be returned to the consumer by the meter reader when the coin box is cleared.

The fixed-charge element in the Sangamo meter consists of a detachable unit comprising a train of wheels driven at one end by a small synchronous motor and terminating in a wheel driving on to the debiting portion of the coin-freed mechanism. A front view of the unit attached to the coin-freed mechanism is shown in the top right-hand corner of Fig. 77. Three dials are provided, the one on the right indicating the amount of the fixed charge in shillings per week which

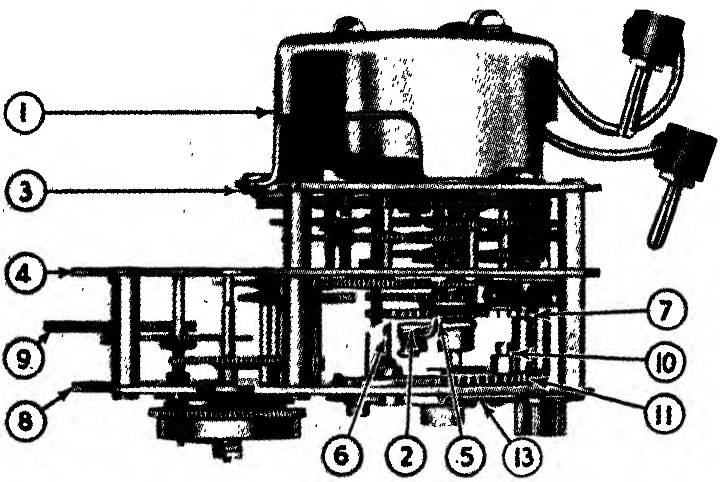


FIG. 79.—Fixed-charge element in Sangamo prepayment meter.

the meter is set to collect and the one on the left indicating the amount of debit, if any, in terms of shillings arrears. The small dial in the middle, consisting of an index and a fixed scale, is provided for testing purposes.

A synchronous motor drives, through appropriate gearing, a rotating arm which makes one revolution per twenty-four hours. The extremity of the arm carries a pawl, the path of which lies around the circumference of a ratchet wheel mounted loosely on the arbor to which the arm is secured. The pawl, which is attached to the arm by a friction-tight joint, is capable of movement and during each revolution of the arm, the pawl encounters two stops, one fixed and one adjustable.

These stops serve to engage and disengage the pawl from the ratchet wheel and during the period of engagement the latter will rotate with its driving arm. The movement which is communicated to the ratchet wheel is transferred through intermediate gearing to the debit side of the differential gear in the coin-freed mechanism.

The method of adjusting the amount of fixed charge collected per week may be followed by reference to Fig. 79. A synchronous motor (1) drives a rotating arm (2) through reduction gears located between plates (3) and (4), the arm making one revolution in an anti-clockwise direction per twenty-four hours. A pawl (5), attached by a friction-tight joint to the arm, encounters a fixed stop (6) once in each revolution and engages with a ratchet wheel (7) which has forty-eight teeth. The ratchet wheel is carried forward, and through gearing supported between plates (4) and (8) rotates wheel (9), from which point the motion is communicated to the debit side of a differential in the coin-freed mechanism. The pawl (5) continuing its travel, encounters in due course an adjustable stop (10) secured to a wheel (11) which is rigidly secured to the dial (13) of the "Shillings per Week" indicator. The adjustable stop causes the pawl to disengage from the ratchet wheel which then remains stationary until the pawl again meets the fixed stop, whereupon the cycle of operations is repeated.

The position of the adjustable stop can be set by means of a screwdriver inserted through a small aperture in the meter cover, immediately below the "Shillings per Week" indicator. The aperture is normally inaccessible until the coin box is removed and the adjustment can only be made by a representative of the supply authority. Three alternative scales are available, covering ranges of ½d. to 1s. 10½d. per week in ½d. steps, 1d. to 3s. 9d. per week in 1d. steps, and 2d. to 7s. 6d. per week in 2d. steps respectively.

It will be noted from the foregoing description and the illustration in Fig. 77 that separate credit and debit indicators are provided; credit being shown as "Units Unused" on the coin-freed mechanism, and debit as "Shillings Arrears" on the fixed-charge element. So long as the meter is in credit the amount will be shown on the credit indicator, and the index of the debit indicator will point to zero. At the moment when credit is exhausted, both indicators will be at zero and the switch will open. The debit side of the differential in the coin-freed mechanism having reached the end of its travel, it is not possible for further motion to be communicated to it in the debit direction, and as the synchronous motor in the fixed-charge element is still running, means must be

provided for the drive to continue; this provision is made in the debit indicator which consists of a revolving index and dial. Immediately credit is exhausted the wheel (9) in the fixed-charge element can no longer transmit motion to the coin-freed mechanism and the motion derived from the ratchet wheel (7) is stored in a spring contained in a recess behind the "Shillings Arrears" dial. Normally the dial and index revolve together, the index being at zero, but when credit is exhausted the dial remains stationary while the index continues to rotate. A spring coupling between the index and dial is wound up and can store up to twenty shillings arrears. When in due course sufficient coins are passed through the mechanism to cancel the debit, the spring is run down until the debit indication reaches zero; any further coins inserted at this stage will re-establish credit and will re-close the switch.

6.11. Chamberlain and Hookham Prepayment Meter, Dual-Coin Two-Part Tariff. A Chamberlain and Hookham two-part tariff prepayment meter, Type J.P.M.V. suitable for dual-coin operation is shown with cover removed in Fig. 80. The main features of the coin-freed mechanism are similar to those described in Section 6.5, the coin receiver, the coin register, the price-change unit and the switch being the same. It differs in the constructon of the differential gears, the credit indicator, and the addition of the fixed-charge element. As will be seen in the illustration the credit indicator is in the form of a continuous scale, indicating money values, the credit portion printed in black reading up to five shillings unused and the debit portion printed in red to fifteen shillings arrears. The fixed-charge element in the form of a detachable unit is shown removed from the meter in Fig. 81.

A two-part tariff meter requires two differential gears in order to summate the debits arising from the operations of the energy element and the fixed-charge element with the credits arising from coins prepaid. In the Chamberlain and Hookham meter the two differentials are combined into one unit mounted co-axially on a single arbor carrying the index of the credit indicator at the forward end and the switch trip-pin at the rear. When the credit indicator is moving from the credit to the debit condition the switch is tripped as the index moves through the zero position. From this point onwards the switch tripping device is arrested and if no coins are inserted the index will continue to move until fifteen shillings arrears are registered. Thereafter, although the fixed-charge element continues to operate, no further debit will be shown. This condition is brought about by the slipping of a friction-drive incorporated in the gear unit which communicates the

drive from the fixed charge element to the differential. Thus, no damage can be caused to the gears if for any reason the meter is allowed to run into debit for a prolonged period.

The fixed-charge element shown in Fig. 81 consists of a self-contained unit which can be attached to or removed from the coin-freed mechanism without the necessity for disturbing any part of the latter

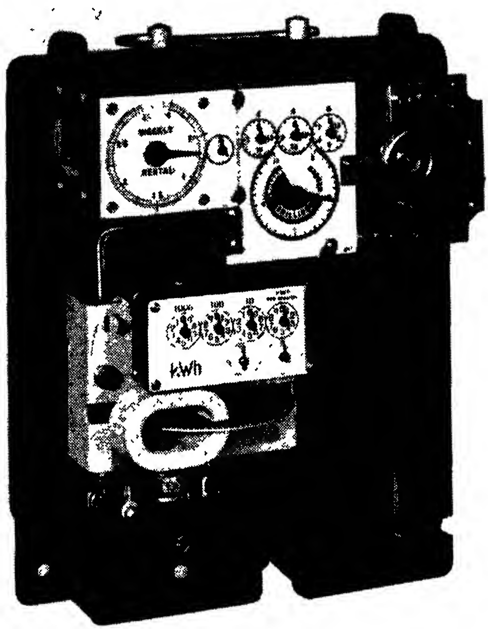


FIG. 80.—Chamberlain & Hookham dual-coin two-part tariff prepayment meter. Type JPMV.

other than removing or replacing two screws. It comprises a train of gears, driven at the one end by a small synchronous motor on the back-plate, and terminating at the other end in a pinion which can mesh with a wheel in the coin-freed mechanism. The front plate of the element is provided with a scale showing the rental charge from 0 to 3 shillings per week in halfpenny steps. An adjustable index can be set to any position on the scale between these limits by means of a screw-driver engaging with a slotted projection immediately below the scale. This slotted projection is accessible through an opening, which can be

sealed, in the meter cover. If preferred by the supply authority, the adjustment may be made by means of a key instead of a screwdriver. To permit this alternative the slotted projection is removable and a squared arbor will be found below as shown in Fig. 80. Where it is desired to collect a higher weekly rental, two interchangeable units are available, the one scaled 0 to 6 shillings per week in penny steps, and the other scaled 0 to 12 shillings per week in twopenny steps.

Immediately behind the front plate and concentric with the rental

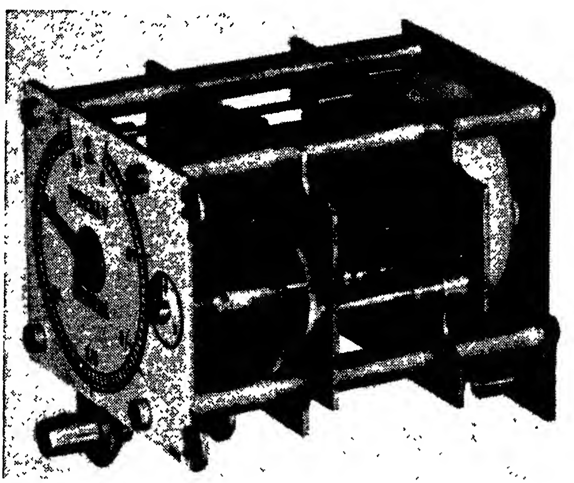


FIG. 81.—Fixed-charge element in Chamberlain & Hookham prepayment meter.

scale is a toothed wheel having an annular projection on its rearward face. This projection has a radial slot cut in one position, and the wheel can be adjusted by turning the squared arbor previously referred to. The annular projection functions as a cam, the working face of which lies in a plane parallel to the front plate; the index associated with the scale is in fixed relationship to the slot in the cam face. The wheel and cam do not move except for the purpose of adjusting the index. An arbor co-axial with the index, and driven by the synchronous motor at a speed of one revolution per hour, carries at its forward end a radial arm, the tip of which rests on the cam face under spring pressure. Once per hour the tip of the arm drops into the slot in the cam face and as rotation of the arm continues steadily the tip rises again.

Mounted on the rotating arm and projecting towards the rear is a pin which acts as a driving dog to carry round a reciprocating wheel loosely mounted on the arbor. This wheel is urged by a spring to rest against a fixed stop, but the driving dog on the rotating arm can engage with a projecting pin on the wheel and carry it away from its position of rest. The angular movement imparted to the reciprocating wheel depends upon the position of the slot in the cam face, and when the tip of the arm drops into the slot, the driving dog disengages and the wheel flies back to its position of rest. Thus, each hour, the reciprocating wheel makes an excursion in the forward direction under the influence of the driving arm and flies back to zero when released. During the forward movement the synchronous motor is driving the differential in the coin-freed mechanism and increasing the debit; a ratchet and pawl device prevents any reversal of the differential during the flyback and no forward movement takes place during the interval following the flyback until the radial arm again engages with the driving pin on the reciprocating wheel.

A testing index is provided on the fixed-charge element to enable a rapid check to be made of the amount registered. The index is located on the right of the weekly rental scale. The test index will register in one hour, the amount which will be debited in one week. Thus, if the fixed-charge element is set to collect two shillings per week the test index will advance two shillings in one hour. Provision is also made for disconnecting the drive between the synchronous motor and the reciprocating wheel, in order that the whole of the gearing up to the credit indicator in the coin-freed mechanism may be tested by hand, a knurled disc mounted on one of the arbors being fitted for this purpose. A small opening at the top of the dial in Fig. 81 (not shown in Fig. 80), permits an observation to be made of the working of the synchronous motor. A small flag carrying a red dot is moved backward and forward past the opening fifty times per minute on a fifty c/s supply. This flag is actuated by a pin on the first wheel driven by the synchronous motor. When the motor is working, the number of times the dot falls past the opening per minute corresponds to the frequency of the supply in cycles per second.

A more recent example of the Chamberlain and Hookham two-part tariff prepayment meter is constructed in a case in which the energy element is isolated from the coin-freed mechanism. When the meter cover is in position, a barrier of insulating material divides the case into two compartments. A wheel in the energy register projects a short

distance through a narrow slit in the barrier and gears up to the coin-freed mechanism. A hinged cover which can be opened gives complete access to the whole of the mechanism without giving access to the energy element; the mechanism can be entirely removed if desired for

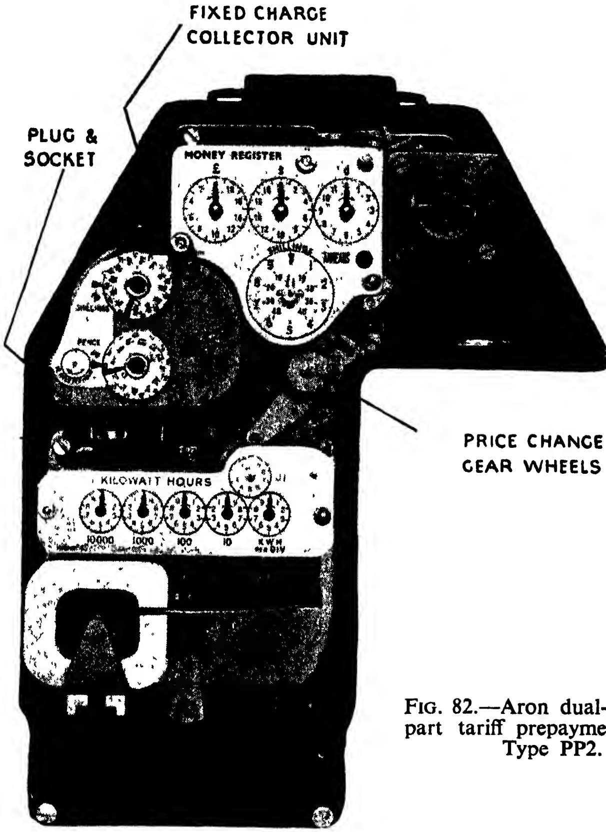


FIG. 82.—Aron dual-coin two-part tariff prepayment meter. Type PP2.

examination. A switch having massive silver-faced contacts and rated at 50 amperes is now available in place of the mercury switch hitherto supplied.

6.12. Aron Prepayment Meter, Dual-Coin, Two-Part Tariff. The Aron two-part tariff prepayment meter, Type PP2, is shown with cover removed in Fig. 82. This meter, which is housed in a case of moulded

insulating material, is of the dual-coin pattern and operable by pennies and shillings. The energy element is located in the lower half of the case with the coin-freed mechanism in the upper portion; the coin receiver is on the extreme right, with the coin register alongside. The credit indicator is below the coin register and the fixed-charge element is on the left, immediately above the energy element. The price-change gear unit for altering the price per kWh is between the energy register and the credit indicator; the coin box occupies a position to the right of the energy element and below the coin receiver.

The operation of the coin receiver may be explained by reference to Fig. 83. A coin drum (3), consisting of a cylinder having a vertical slot for the reception of a coin is rigidly connected to a hollow brass trunnion shaft (28). An operating handle (1) is secured to the forward end of the coin drum. A spring-loaded plunger (30) carries a radial peg (17) which is free to move longitudinally in a slot through the trunnion. Freely mounted on the end of the trunnion is a gear-wheel carrier, shown partly cut away in Fig. 83 (*a*) to expose a section of the trunnion, and removed from the trunnion in Fig. 83 (*c*). This carrier consists of a circular disc (20) carrying two shouldered pins (8) and supporting a toothed wheel (12). The wheel can slide along the two pins but is held normally against the shoulders on the pins by two compression springs (16); a hole through the centre of the wheel permits both axial and rotary movement independently of the trunnion.

Before a coin can enter the coin drum the operating handle (1) must be turned in an anti-clockwise direction as seen from the left of the illustration; this action causes the peg (17) to travel along the surface of an inclined plane (13), and moves the spring-loaded plunger (30) to the right. It also moves the toothed wheel (12) to the right, at the same time compressing the springs (16). The tip (5) of the plunger (30) is withdrawn from the coin drum (3) leaving sufficient space for a penny to enter. On inserting a coin (say for example a shilling, as shown at (2) in Fig. 83 (*a*) and 83 (*b*), and turning the operating handle in a clockwise direction, the radial peg (17) moves down the inclined plane (13) from right to left; the toothed wheel (12) and the plunger (30) also move to the left, until arrested by the tip (5) of the plunger coming into contact with the edge of the coin (2). Further turning of the operating handle causes the peg (17) to engage with the upper shouldered pin (8) thus rotating the gear-wheel carrier; when the coin drum has rotated through 120 deg. or thereabouts, the peg (17) meets another inclined plane (10), causing the peg to move again to the right, together

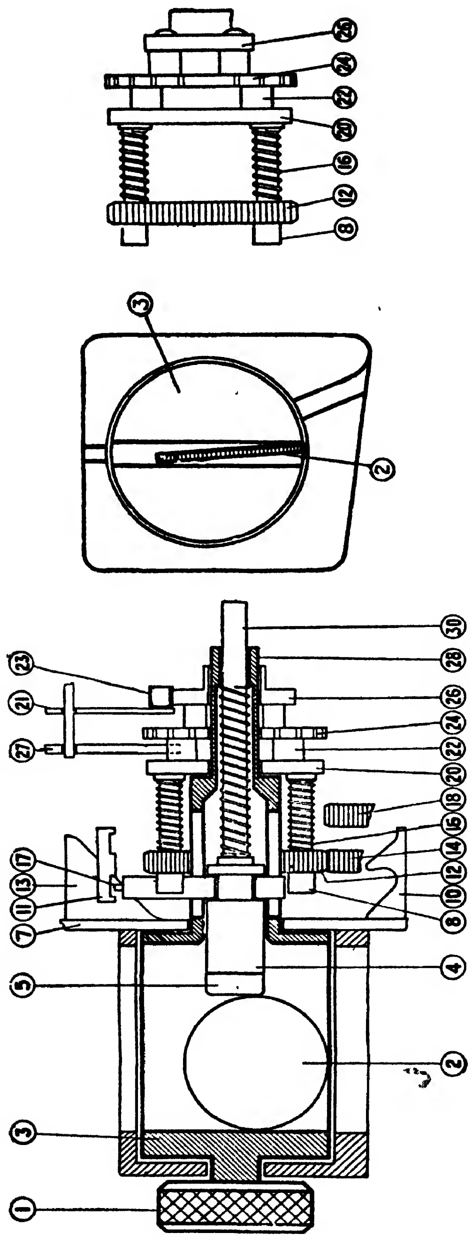


FIG. 83.—Arrangement of coin-receiver in Aron dual-coin prepayment meter.

with the plunger; this releases the coin and allows it to fall through the coin outlet into the coin box.

The position occupied by the toothed wheel (12) during the rotation of the coin drum (3) depends upon the diameter of the coin in the drum. If no coin is inserted and the operating handle is turned, the spring-loaded plunger will move to its fullest extent to the left and the radial peg (17) will be carried beyond the extremities of the shouldered pins (8). Thus the trunnion shaft will be free to turn without being coupled to the gear-wheel carrier. If a shilling is inserted, the position of the toothed wheel (12) will be such that it is in engagement with a wheel (14) and the rotation of this pair will advance the credit side of the differential gear in the prepayment mechanism by an appropriate amount. If a penny is inserted, the spring-loaded plunger will have a shorter travel and the toothed wheel (12) will engage a wheel (18). In this case the gear ratio between the gear-wheel carrier and the differential will be different, and the advance of the credit side of the differential will be only one-twelfth of the amount communicated when a shilling is inserted.

The insertion of a coin, the diameter of which differs substantially from that of a penny or shilling, will prevent rotation of the gear-wheel carrier. The rejection of unsuitable coins is effected by a gate (11) lying in the path of the radial peg (17). Slots in the gate permit the tip of the peg to pass when coins of the correct diameter are in the coin drum during rotation, but obstruct the peg in other circumstances. To release unsuitable coins from the coin drum, a button, accessible to the consumer, can be pressed; this enables the coin drum to be turned backward through an angle sufficient to allow the coin to slide through the coin outlet into the coin box.

The passage of a penny or a shilling through the coin receiver in the normal manner causes the toothed wheel (12) to turn through half a revolution. A double-throw cam (26) attached to the gear-wheel carrier has a spring-loaded roller (23) riding on its periphery. Pressure on the roller brings the carrier to rest in a definite position after each operation and a ratchet wheel (24) prevents the carrier from being turned backwards, once a forward movement has been initiated. One of two pins (22) on the carrier co-operating with a lever (27), actuates the switch-closing device when a credit is first established.

The fixed-charge element is in the form of a detachable unit which can be removed by slackening off three screws and disconnecting a plug and socket connection. The complete unit is shown in Fig. 84.

It is provided with two setting dials for adjusting the amount of fixed charge collected weekly. The upper dial is adjustable from zero in steps of 6d. up to a maximum of 11s. 6d., and the lower dial from zero in steps of $\frac{1}{4}$d. up to 5$\frac{3}{4}$d. Taken together, it is possible to vary the fixed charge from zero in steps of $\frac{1}{4}$d. up to a maximum of 11s. 11$\frac{3}{4}$d. per week. The setting dials are adjustable by means of a screwdriver inserted through two holes in the meter cover; the holes are normally closed by a small sealing piece and can be exposed by removing the seal and turning the sealing piece. A testing index on the left makes twelve revolutions per hour when the synchronous motor which drives the mechanism is running at its normal speed of 200 revolutions per minute. This gives an indication from the exterior of the meter that the motor is running at the correct speed.

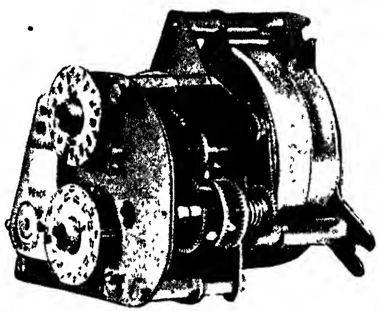


FIG. 84.—Fixed-charge element in Aron two-part tariff prepayment meter.

The synchronous motor drives through a train of wheels on to a crank, coupled through a connecting rod to a toothed sector. The crank, rotating at a constant speed, causes the toothed sector to move backwards and forwards at regular intervals. An arbor geared to the sector carries a radial arm, and each reciprocation of the sector results in a corresponding reciprocation of the radial arm, the arc of movement being substantially 360 deg. Thus, the rotary motion of the motor shaft is converted into reciprocating motion of the radial arm.

Two setting wheels loosely mounted on the arbor, one on each side of the radial arm, have each an inwardly projecting peg lying in the path of the radial arm as it makes its forward excursion. The two wheels are associated with the two setting dials and the position of the pegs relative to the radial arm can be set by turning the dials. If both dials are set to zero the radial arm in its forward excursion will approach

the pegs and will contact them at the end of its travel, but will not move the setting wheels. If the dials are set to the full-scale reading the radial arm will contact the pegs at the commencement of its forward excursion, and will push forward the setting wheels through the full distance. For intermediate settings of the dials the setting wheels will be pushed forward by proportionate amounts.

The forward movement communicated to the two setting wheels is transferred through gearing to a differential which sums up the total amount to be passed on from the fixed-charge element to the debit side of the coin-freed mechanism. Each setting wheel is urged by a spring to move in the reverse direction, and as the radial arm makes its backward excursion, the setting wheels follow up to a point determined by the position of the setting dials. A ratchet and pawl between each setting wheel and the differential in the fixed-charge element prevents any movement being communicated to the differential on the backward excursion of the radial arm. Thus, the continuous rotary movement of the synchronous motor is converted into an intermittent unidirectional drive of adjustable amount, for transmission to the debit side of the differential in the coin-freed mechanism. The final drive from the fixed-charge element is through a friction clutch which can slip and thus prevent damage to the gearing if, for any reason, the accumulated debit exceeds that for which the debit indicator is constructed.

The credit indicator consists of two concentric scales and two pointers, one large and the other small, arranged like the hands of a clock. One revolution of the large pointer around the outer scale, corresponds to a credit of ten shillings. The figures for this scale are visible through small circular openings in the dial plate. The small pointer operates over an inner circle of figures and indicates up to a maximum of forty shillings. When the meter is in credit, the figures in the small circular openings are black, and read in an anti-clockwise sequence. In addition, a small rectangular opening exposes the word "CREDIT" in black. When the meter is in debit, the figures appearing in the small circular openings automatically change to the opposite sequence and appear in red. Also the word "CREDIT" in black changes to the word "ARREARS" in red. The small inner scale has a centre zero and figures in an anti-clockwise direction starting from zero are printed in black, representing credit. The figures in a clockwise direction represent arrears and are printed in red. The maximum scale indication in each direction is forty shillings.

6.13. Metropolitan-Vickers Prepayment Meter, Dual-Coin, Two-Part Tariff. The Metropolitan-Vickers two-part tariff prepayment meter, Type RU1, is shown with cover removed in Fig. 85. It comprises the combination of a single-phase energy element with a coin-freed mechanism suitable for dual-coin operation and a fixed-charge element, the whole being housed in a case of moulded insulating material. A single-rate dual-coin prepayment meter manufactured by Metropolitan-Vickers and incorporating a coin receiver for dual-coin operation has

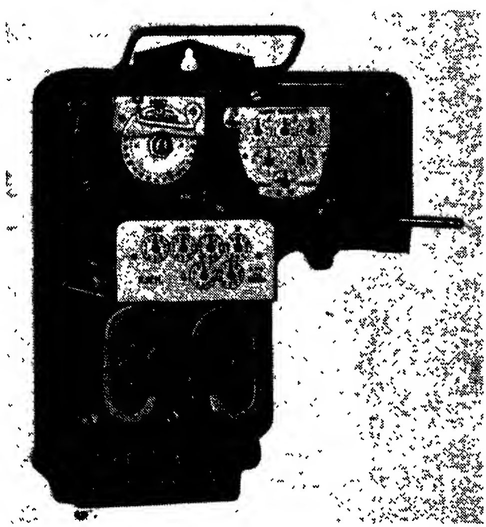


FIG. 85.—Metropolitan-Vickers dual-coin two-part tariff prepayment meter. Type RUI.

been described in Section 6.6. and details of the coin-receiver mechanism will not be repeated here. As will be seen from Fig. 85 the energy element occupies the lower portion of the case with the fixed-charge element immediately above the energy register, and the coin-freed mechanism is on the right. The coin box occupies the space to the right of the energy element and below the coin-freed mechanism.

The coin register showing the value of the coins inserted has three indices, indicating pounds, shillings and pence, to a total value of ten pounds. The credit indicator also has three indices, the upper two of which are scaled in a clockwise direction to indicate credit in pence and shillings respectively. The third and lower scale has a centre zero and

indicates coins prepaid over the right half to a total value of twenty shillings. When credit is exhausted the switch opens and all three indices will then point to zero. During the registration of debit, all three indices move in an anti-clockwise direction and the lower index then works over the left half of the scale which is marked "OWING". An inner circle of figures is provided on the two upper scales for the debit indications and the lower index can register a total debit of twenty-five shillings.

The fixed-charge element consists of a train of wheels driven by a

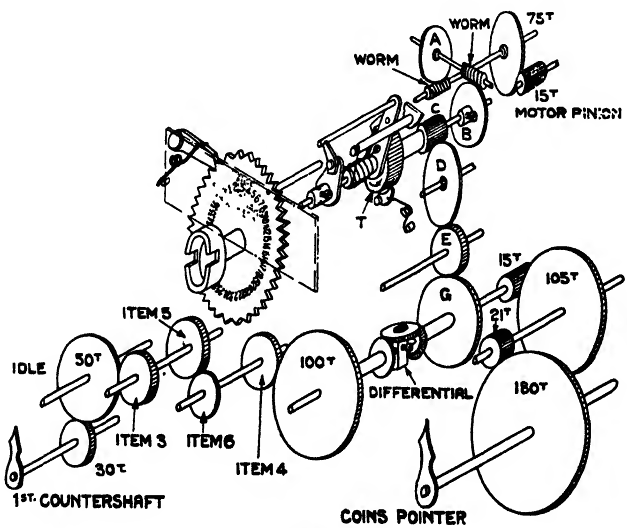


FIG. 86.—Arrangement of gearing in fixed-charge element of Metropolitan-Vickers prepayment meter.

small synchronous motor, the arrangement of the gearing being as shown in Fig. 86. A worm wheel *B* is mounted on the rearward end of an arbor, the forward end of which carries a rotating arm having a spring-controlled pawl at its extremity. Loosely mounted on the same arbor is a ratchet wheel *T* and a pinion *C*. Resting against a fixed stop is a spring-controlled fly-back lever co-axial with the rotating arm and carrying a long driving pin which lies in the path of the pawl on the rotating arm. This fly-back lever also carries a pawl which engages the ratchet wheel *T* to drive in an anti-clockwise direction. An adjustable trip-pin secured to the rear face of the fixed-charge indicator also

lies in the path of the pawl on the rotating arm. The fixed-charge indicator consists of a notched disc carrying a dial plate on its face; the amount in pence of the fixed charge per week can be set by turning the disc, and is shown in an opening at the top of the mechanism.

The fixed-charge element operates in the following manner. The synchronous motor, driving the worm wheel *B* through intermediate gearing, rotates continuously the arm which carries the spring-controlled pawl at its extremity. Once in each revolution this pawl engages the pin on the fly-back lever, carrying it forward in an anti-clockwise direction. The ratchet wheel *T* together with the pinion *C* are driven in the forward direction by the pawl on the fly-back lever. In due course the pawl on the rotating arm meets the trip-pin on the fixed-charge indicator plate and further movement of the arm then deflects the pawl, causing it to release the fly-back lever and allows it to return to its initial position against a stop. Thereafter, until the pawl in the rotating arm again engages the pin on the fly-back lever, the pinion *C* remains stationary. This cycle of operations is repeated continuously and it will be noted that the greater the angular distance separating the trip-pin on the indicator plate from the pin on the fly-back lever the greater will be the motion communicated from the synchronous motor to the pinion *C* in each revolution of the rotating arm.

The energy element and the fixed-charge element act jointly through a differential gear to move the credit indicator in the debit direction. In the diagram, the credit indicator is represented by the "Coins pointer" on the right, and an arbor in the energy register is represented by the "1st countershaft" on the left. A train of wheels between the energy register and the differential includes "Item 5" and "Item 6". The latter are removable and form part of the price-change gear unit which enables the price per kWh to be altered when desired. When credit is exhausted, the fixed-charge element alone drives through pinion *C* and the wheels *D* and *E* on to the wheel *G* and thence through one side of the differential, to indicate a debit on the credit indicator.

The maximum amount of fixed charge to be collected weekly can be varied by exchanging the fixed-charge element. Gearing together with suitable scales are available for collecting the following amounts:—

(*a*) ½d. to 2s. per week in half-penny steps.
(*b*) 1d. ,, 3s. ,, ,, ,, one ,, ,,
(*c*) 1d. ,, 4s. ,, ,, ,, one ,, ,,
(*d*) 2d. ,, 6s. ,, ,, ,, two ,, ,,

The setting of the fixed charge is accomplished by inserting a screw-driver through an opening in the meter cover; the screw-driver engages a slot in the centre of the dial plate and after the adjustment is made the opening can be sealed to prevent unauthorized access.

The time required for the rotating arm to make one revolution, i.e., the time cycle, differs in each of the foregoing gear trains and is as

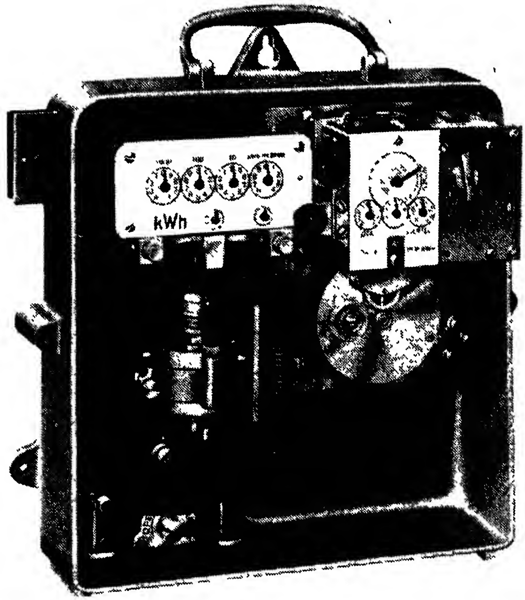


FIG. 87.—Chamberlain & Hookham direct-current two-part tariff prepayment meter.

follows:—(*a*) 168 minutes, (*b*) 144 minutes, (*c*) 84 minutes, (*d*) 72 minutes. In addition to the four fixed-charge elements already referred to, a wide-range element has been developed having two independently adjustable dials to indicate the fixed charge. This double-dial element can be set to collect amounts from ¼d. per week to 8s. 9d. per week in steps of one farthing.

6.14. Chamberlain and Hookham Prepayment Meter, Direct-Current, Two-Part Tariff. Although the use of direct current for domestic supplies has almost ceased in this country, a brief description of a

direct-current two-part tariff prepayment meter is included as a matter of historical interest. One of the few types developed was the Chamberlain and Hookham meter shown in Fig. 87, with cover removed to expose the interior. It comprises the combination of the well-known mercury-motor ampere-hour meter with a coin-freed mechanism of the single-coin variety and a fixed-charge element consisting of an electrically-wound clockwork mechanism.

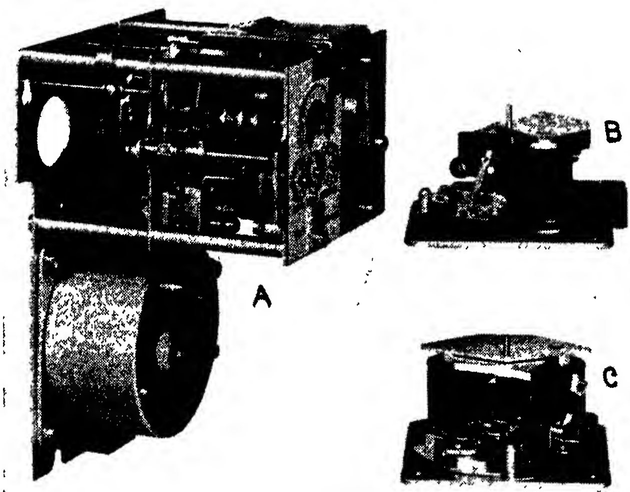


FIG. 88.—Fixed-charge element in Chamberlain & Hookham direct-current two-part tariff prepayment meter.

The coin-freed mechanism is of simple construction and calls for little comment. It comprises a coin receiver of the type illustrated in Fig. 55 (page 140) and a mercury switch of the tubular pattern having two contacts bridged by a pool of mercury when in the closed position. The price per kWh is varied by means of a price-change gear unit, conveniently accessible at the top of the mechanism when the meter cover is removed, and self-locating when the unit is replaced. As the energy element (the ampere-hour meter in this instance) is alive at mains voltage the gearing connection between the meter and the coin-freed mechanism is made through a bakelite gear wheel in order to insulate the mechanism. A steady pin on the front of the energy register engages with an insulating bush in a steady plate secured to the

mechanism and serves to maintain the latter in correct gear relationship with the meter at all times.

Two differential gears are mounted co-axially on the arbor carrying the index of the credit indicator and may be seen in the side view of the coin-freed mechanism shown in Fig 88A. The differential at the rear summates the two debits arising from the joint actions of the energy element and the fixed-charge element. The total debit is transferred to the rear crown-wheel of the forward differential and the forward crown-wheel deals with the credit arising from the insertion of coins. The arbor carrying at its forward end the index of the credit indicator, carries at its rearward end the switch trip-pin which opens the switch when credit is exhausted. The fixed charge is varied by means of a second price-change gear unit located below the differential and accessible when the meter cover is removed.

The fixed-charge element is contained in a circular brass case below the coin-freed mechanism and may be removed as a single unit by disconnecting two wires and withdrawing four screws. A close-up view of the element may be seen in Fig. 88B, together with two views with the cover removed to expose the interior. It comprises a bipolar electromagnet energized from the supply mains and having a flat armature on which two salient poles are formed. The armature is mounted so that it can turn through a limited angle when the electromagnet is energized; a tension spring normally holds the armature at the outward limit of its movement which is determined in each direction by buffer stops. Fitted to the armature and moving with it is a sleeve carrying a small ratchet wheel, the pawls of which are supported by a larger ratchet wheel immediately underneath. This larger ratchet wheel in turn has pawls mounted on the train plate and forms one half of the mainspring barrel, the inner end of the mainspring being attached to it. The outer end of the mainspring is attached to the lower half of the barrel, the outside of which carries a toothed wheel driving through two intermediate gears on to a fully-jewelled lever escapement.

The electromagnet circuit is controlled by a "tip-over" contact mechanism mounted on an insulating block fixed to the back-plate. The mainspring is normally maintained in a nearly fully-wound condition and as it runs down under the control of the escapement a contact arm is pushed over a dead centre by the armature, causing the electromagnet circuit to be completed. The armature is immediately attracted, pushing the contact arm back over the dead-centre into its open-circuit position. The mainspring when fully wound will run the

clock for two hours in the event of a temporary interruption of the supply. Following an interruption the armature will reciprocate until the spring is again fully wound, after which, a rewind occurs at short intervals. The clock drives through gearing mounted outside the cover on to the price-change gear unit and thence to the differential. For testing purposes, a wheel on the clock cover can be disengaged from the clock train and driven by a wheel having a knurled flange turned manually, thus enabling the fixed charge mechanism to be rapidly checked.

CHAPTER VII

POLYPHASE KILOWATT-HOUR METERS

7.1. Measurement of Polyphase Energy. Power distribution through polyphase circuits is, in Britain, confined mainly to three-phase systems, although two-phase distribution is employed to a small extent. The methods of measuring polyphase power or energy are basically the same as those used in single-phase measurements, but there is much greater diversity in the types of instrument used to meet the varied conditions which arise in practice. In single-phase circuits the meters employed register in kilowatt-hours in most cases, but in polyphase circuits the measurement of the lagging or leading components of the current and also the kilo-volt-ampere-hours may be necessary in addition.

All polyphase systems may be regarded as a collection of single-phase systems operating in synchronism but with a definite phase-displacement between each. The energy consumption can be registered by a collection of single-phase meters, one in each phase, but for practical convenience, multi-element meters are usually adopted. In polyphase distribution it is not usual to provide two conductors for each phase. Instead, the number of conductors may be limited to one per phase, plus a common return conductor for all the phases. An exception to this general rule occurs in the case of two-phase four-wire systems. For any number of phases in excess of two, the number of conductors can be reduced to one per phase. The number of single-phase meter elements required to measure the energy consumption in a polyphase circuit is, in general, one less than the number of conductors.

7.2. Polyphase Distribution Systems. The polyphase distribution systems in use are two-phase three-wire, four-wire or five-wire, and three-phase three-wire or four-wire. The two-phase systems are frequently used abroad but seldom in this country. All high voltage distribution in Britain is three-phase three-wire. Low voltage distribution is by means of three-phase three-wire for power and three-phase four-wire for mixed power and lighting loads.

The two-phase system comprises two single-phase systems supplying two currents having a relative phase displacement of a quarter of a period or 90 deg. The current may be distributed over three, four or

five wires and the arrangement of the circuits is shown in Fig. 89. In the two-phase three-wire circuit shown in Fig. 89 (a), the red and blue phases R and B are joined together at the neutral point N. The voltages v_R v_B between the lines and neutral are nominally equal, but are displaced in phase by 90 deg. The voltage between the two lines R B is equal to the vector sum of these lines to neutral voltages, and is $\sqrt{2}$ times the voltage between either line and neutral, that is:

$$V_{RB} = \sqrt{2} \times v_R = \sqrt{2} \times v_B$$

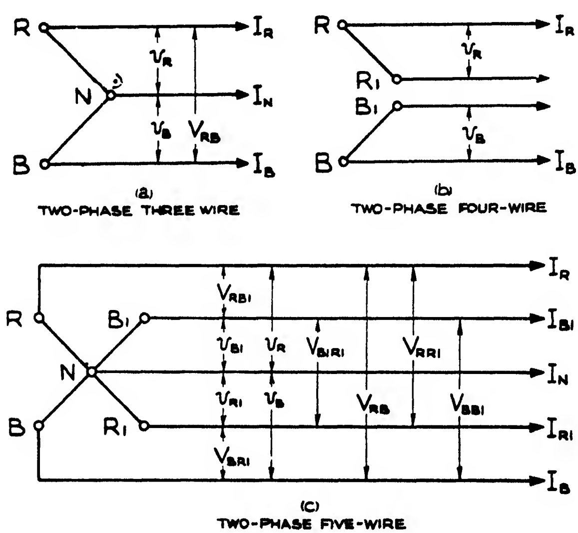


FIG. 89.—Diagram representing two-phase distribution systems.

With balanced loads connected between lines and neutral, the line currents I_R I_B will be equal but will be displaced in phase by 90 deg. The current I_N in the neutral is the vector sum of the currents in the lines and is $\sqrt{2}$ times the line current, that is:

$$I_N = \sqrt{2} \times I_R = \sqrt{2} \times I_B$$

This relationship will not be maintained if the loads are unbalanced or if the power-factor of one differs from that of the other.

The two-phase four-wire system shown in Fig. 89 (b) is seldom used. It differs from the two-phase three-wire system in that there is no common or neutral conductor, the two phases being entirely separated electrically.

The two-phase five-wire system shown in Fig. 89 (c) is very flexible and adaptable, and permits a supply to be given at any one of three different voltages. It consists of a red phase R $R1$ and a blue phase B $B1$ each having a mid-point tapping at N. In effect, these constitute two single-phase three-wire supplies, displaced in phase by 90 deg., but joined together at their mid-points N. The voltages between each outer conductor and the neutral are equal, that is to say:

$$v_{B1} = v_{R1} = v_B = v_R = v$$

Similarly the voltages between consecutive pairs of outer conductors are also equal, one to another, as:

$$V_{RB1} = V_{B1R1} = V_{R1B} = V_{BR} = V$$

Since each of these is the vector sum of two voltages displaced 90 deg. in phase, the voltage V between consecutive pairs of outer conductors is equal to $\sqrt{2}v$ or 1·414 times the voltage between the neutral and any outer conductor. Also, the voltage between pairs of diametrically opposite outer conductors is the sum of two voltages in phase, thus:-

$$V_{RR1} = V_{BB1} = 2v$$

From the foregoing it will be seen that from a two-phase five-wire supply three different voltages may be obtained having values proportional to v, $\sqrt{2}v$ and $2v$ respectively. Examination of Fig. 89 (c), will reveal that ten separate single-phase supplies are available, namely, four at voltage v, four at voltage $\sqrt{2}v$ and two at voltage $2v$. Further, four separate two-phase supplies may be taken at a voltage v between line and neutral and four similar supplies at a voltage $\sqrt{2}v$ between line and common conductor. With balanced loads there will be no current in the neutral conductor, but if the loads are unbalanced there will be a neutral current the magnitude of which will depend upon the state of unbalance, and the power-factor.

The three-phase system comprises three single-phase systems supplying three currents having a relative phase displacement of one third of a period or 120 deg. The current may be distributed over three or four wires and the arrangement of the circuits is shown in Fig. 90. In the three-phase three-wire circuit shown in Fig. 90 (a) the windings of a generator or transformer are shown connected in delta. If the voltages between lines are displaced 120 deg. apart and are equal, then

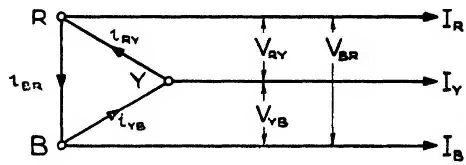
$$V_{RY} = V_{YB} = V_{BR} = V$$

With balanced loads connected between lines and all having the same power-factor, the line currents will also be displaced in phase by 120 deg. and will be equal, so that

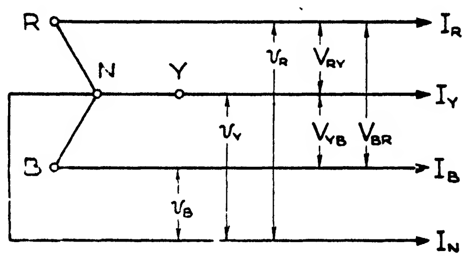
$$I_R = I_Y = I_B = I$$

The current in each line is the resultant of the currents in two of the phases of the generator or transformer. The phase currents will also be equal, that is:

$$i_{RY} = i_{YB} = i_{BR} = i$$



(a)
Three-phase three-wire delta connection.



Three-phase four-wire star connection.

FIG. 90.—Diagram representing three-phase distribution systems.

The line current I is equal to $\sqrt{3}$ times the current i in each phase, so that:

$$I = \sqrt{3} \times i$$

This relationship will not be maintained if the loads are unbalanced or if the power-factor of one differs from that of the others.

In the three-phase four-wire circuit shown in Fig. 90 (b) the windings of the generator or transformer are shown connected in star. One end of each phase winding is connected to a common junction N forming the neutral point of the system, and the remaining ends are connected to the lines R Y B. The line to neutral voltages are displaced 120 deg. apart and are equal. Thus:

$$v_R = v_Y = v_R = v$$

As in the case of the three-phase three-wire system the voltages between lines are also equal and are:

$$V_{RY} = V_{YB} = V_{BR} = V$$

The voltage V between any pair of lines is equal to $\sqrt{3}$ times the voltage v between any line and the neutral N. Thus:

$$V = \sqrt{3} \times v$$

In a three-phase four-wire system, the current in each line is the same as in the corresponding phase winding of the generator or transformer. With balanced loads all having the same power-factor the line currents will be equal and will be displaced in phase 120 deg. apart. Then:

$$I_R = I_Y = I_B = I$$

as in the case of the three-phase three-wire system. The load may be connected in star or in delta; if delta-connected, there will be no current returning to the neutral, whether the load is balanced or unbalanced, but if star-connected with the star point joined to the neutral there will be a current in the neutral if the load is unbalanced.

In each phase of a three-phase system, the voltage rises from zero to a maximum value in the positive direction, dies away to zero, rises to a maximum value in the negative direction and again dies away to zero. This cyclic change is repeated at a rate equal to the frequency of the supply in cycles per second, and although the same changes occur in each phase they take place in succession and not simultaneously. The order in which these cyclic changes take place is termed the phase sequence, that is to say, the sequence in which the voltage reaches a maximum value in the three phases.

Phase sequence is of importance in the case of certain types of polyphase meters such as reactive and kilovolt-ampere meters which may be completely inaccurate if the wrong phase sequence is applied. Many well-designed polyphase meters for the measurement of kilowatt-hours are little affected by phase sequence, but small differences in error can be detected by reversal, and in order to eliminate these small errors it is usual for meters to be connected in accordance with a definite phase sequence. According to a convention adopted in this country the standard phase sequence occurs in the order R–Y–B and in the connection diagrams for three-phase meters which illustrate this chapter the lines are identified by these letters. In installations where the phases are coloured for ease in identification of the conductors the colours red, yellow (or white), and blue are adopted, the

initial letters of these colours corresponding to the letters used in the diagrams. It is usual to regard the red as the lagging phase and blue as the leading phase. In vector diagrams the direction of phase rotation is considered as being anti-clockwise and may be indicated by a curved arrow.

7.3. Measurement of Energy in Two-Phase Four-Wire Systems. The measurement of the energy consumption in a two-phase four-wire circuit is accomplished in a very simple manner. Since the two phases are entirely separate, two single-phase meters may be employed as shown in Fig. 91. The current coil of a single-phase measuring element M_R is connected in the red line, the voltage coil being connected across the lines R $R1$. The load on the red phase is represented by L_1.

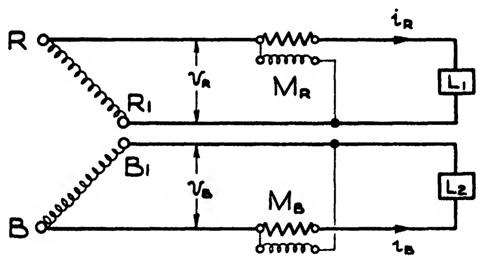


FIG. 91.—Measurement of energy in a two-phase four-wire circuit.

Similarly, the current coil of a single-phase measuring element M_B is connected in the blue line, the voltage coil being connected across the lines B $B1$. The load on the blue phase is represented by L_2. The total energy W expended in the loads $L_1 + L_2$ during a time interval t is given by the expression:

$$W = W_1 + W_2 = (v_R \times i_R \times t \times \cos \phi_R) + (v_B \times i_B \times t \times \cos \phi_B)$$

where W_1 and W_2 represent the watt-hours measured by the measuring elements M_R and M_B respectively, and the terms, $\cos \phi_R$ $\cos \phi_B$ represent the power-factor of each load. If the voltage, current and power-factor are the same in each phase, that is, if the loads are balanced, then the total expenditure of energy in a two-phase four-wire system is equal to:

$$W = 2\,(v \times i \times t \times \cos \phi)$$

If the time interval t is measured in hours, then the energy W will be expressed in watt-hours.

Although two separate single-phase meters may be used to measure the total consumption it is more convenient in practice to use a two-element polyphase meter, as less space will be occupied and there will be only one register to read instead of two. Such a meter will be accurate whether the load is balanced or unbalanced. Where the load is truly balanced a single-phase meter may be employed and the readings on the register multiplied by two, or a similar meter may be used having a register geared to record twice the single-phase energy, thus giving a direct reading on the dial without the use of a constant. A balanced-load meter is not to be recommended as a rule, if the readings are to be used as the basis for charging a consumer, but would be satisfactory for accounting in a factory where the load consists entirely of motors. If any part of the load consists of lighting it is unlikely that the load could be regarded as balanced.

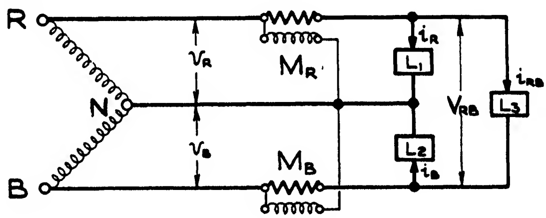


FIG. 92.—Measurement of energy in a two-phase three-wire circuit.

7.4. Measurement of Energy in Two-Phase Three-Wire Systems. The method of measuring energy consumption in a two-phase three-wire circuit is similar to that employed in a two-phase four-wire circuit but the loading conditions may differ. The two-phases are interconnected and have a common return path or neutral as shown in Fig. 92. Because of this interconnection of phases it is now possible to connect a load between the red and blue lines as shown at L_3. The voltage V_{RB} across the load L_3 is $\sqrt{2}$ times the voltage v_R or v_B and the current taken by this load passes through both of the measuring elements M_R M_B of the polyphase watt-hour meter. When current is being supplied to the three loads L_1 L_2 L_3 as shown in Fig. 92 the total energy expended during a time interval t is given by the expression:

$$W = W_1 + W_2 = (v_R \times i_R \times t \times \cos \phi_R) + (v_B \times i_B \times t \times \cos \phi_B)$$
$$+ (V_{RB} \times i_{RB} \times t \times \cos \phi_{RB})$$

It is obvious that if the load L_3 is disregarded, the conditions in

a two-phase three-wire circuit and a two-phase four-wire circuit are identical, insofar as the measuring elements are concerned, but these conditions are modified by the addition of the load L_3. The effect of this load may now be considered as regards its influence on the performance of two single-phase meters at M_R M_B.

When a single-phase non-inductive load as at L_3 is connected between the lines R B, a current i_{RB} in phase with the applied voltage V_{RB} will flow through the current coils of the two single-phase meters M_R M_B. This current will not be in phase with the voltage applied to the voltage coils of the two meters but will be lagging 45 deg. with respect to the voltage in the meter element M_R and leading 45 deg. with respect to the voltage in the meter element M_B. Thus, although the power-factor of the load is unity, the power-factor at which the meter elements are operating is equal to cos 45 deg., that is, 0·707, lagging in the case of M_R and leading in the case of M_B.

The phase relationships at various power-factors may be seen from the vector diagram in Fig. 93. The condition when the power-factor of the load L_3 is equal to unity, is shown by the current vector i_{RB} which is in phase with the voltage vector V_{RB}. But the power-factor at which the meter elements M_R M_B are operating is not unity; the current vector i_{RB} is lagging 45 deg. behind the voltage vector v_R in the element M_R and is leading 45 deg. in front of the voltage vector v_B in the element M_B. It will be seen in Fig. 92 that the direction of current through the current coil of the measuring element M_B due to the load L_3 is reversed relative to the direction through M_R. Because of this the current vector associated with the voltage vector v_B in the element M_B becomes $-i_{RB}$, the minus sign indicating the reversal in phase.

The energy expended in the load L_3 is equal to :

$$W = V_{RB} \times i_{RB} \times t \times \cos \phi_{RB}$$

and as the power-factor in this instance is unity it may be expressed as :

$$W = V \times i \times t$$

This energy is measured jointly by the two meter elements M_R M_B, the total consumption being proportional to :

$$W = W_1 + W_2 = (v_R \times i_{RB} \times t \times \cos 45^\circ) + (v_B \times i_{RB} \times t \times \cos -45^\circ)$$

where W_1 is the registration on the meter element M_R and W_2 the registration on M_B; the minus sign in the term cos -45° indicates

that the current is leading relative to the voltage and as cos 45 deg. and cos -45 deg. both equal 0·707 this expression becomes:

$$W = W_1 + W_2 = (v_R \times i_{RB} \times t \times 0{\cdot}707) + (v_B \times i_{RB} \times t \times 0{\cdot}707)$$

The current is the same in both cases and assuming balanced voltages, it is evident that the total energy registered by the two meters is equal to:

$$\begin{aligned} W &= 2\,(v \times i \times t \times 0{\cdot}707) \\ &= 1{\cdot}414 \times v \times i \times t \\ &= \sqrt{2} \times v \times i \times t \\ &= V \times i \times t \end{aligned}$$

When the power-factor of the load is unity both meters register at the same rate, but at any other power-factor the rates will be different. Take the case where the current in the load L_3 is lagging 45 deg. corresponding to a power-factor of 0·707 (i.e., cos 45°). The energy expended in the load is now:

$$\begin{aligned} W &= V_{RB} \times i_{RB} \times t \times \cos 45^\circ \\ &= V \times i \times t \times 0{\cdot}707 \end{aligned}$$

and the energy registered by the two meter elements M_R M_B is:

$$\begin{aligned} W_1 + W_2 &= [v_R \times i_{RB} \times t \times \cos(45^\circ + 45^\circ)] + \\ &\quad\ [v_B \times i_{RB} \times t \times \cos(45^\circ - 45^\circ)] \\ &= (v_R \times i_{RB} \times t \times \cos 90^\circ) + \\ &\quad\ (v_B \times i_{RB} \times t \times \cos 0^\circ) \end{aligned}$$

But cos 90° is equal to zero, consequently the energy W_1 registered by the meter element M_R is zero; also cos 0° is equal to 1, consequently the energy registered by the meter element M_B is proportional to:

$$\begin{aligned} W_2 &= v_B \times i_{RB} \times t \\ &= v \times i \times t \\ &= V \times i \times t \times 1/\sqrt{2} \\ &= V \times i \times t \times 0{\cdot}707 \end{aligned}$$

The total energy $W_1 + W_2$ registered by the two meter elements is therefore equal to the energy W expended in the load, i.e. $W = V \times i \times t \times 0{\cdot}707$ as previously stated. The condition described above is indicated in Fig. 93 where the vectors i_{RB1} and $-i_{RB1}$ are lagging 45 deg. behind the vectors i_{RB} and $-i_{RB}$ respectively. It will be seen that the current is lagging 90 deg. behind the voltage in the meter element M_R and is in phase with the voltage in the element M_B.

Now consider the case where the power-factor of the load is equal to 0·5, corresponding to a lag of 60 deg. in the current. This is shown in Fig. 93 by the vectors i_{RB2} and $-i_{RB2}$ lagging 60 deg. behind the vectors i_{RB} and $-i_{RB}$ respectively. The current in the meter element M_R is now lagging 105 deg. behind the voltage v_R and in the meter element M_B is lagging 15 deg. behind the voltage v_B. The energy expended in the load is:

$$\begin{aligned} W &= V \times i \times t \times 0{\cdot}5 \\ &= v \times i \times t \times 0{\cdot}5 \times \sqrt{2} \\ &= v \times i \times t \times 0{\cdot}707 \end{aligned}$$

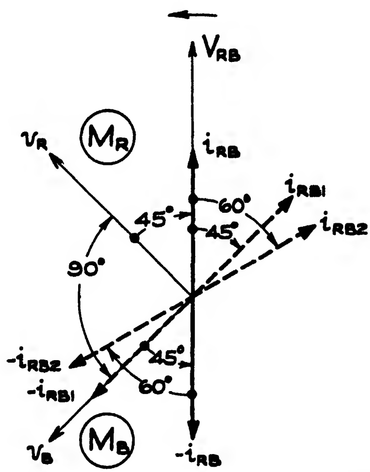


FIG. 93.—Vector diagram showing single-phase load on two-phase three-wire circuit.

The energy registered by the meter elements M_R M_B is:

$$\begin{aligned} W_1 + W_2 &= [v_R \times i_{RB} \times t \times \cos(45° + 60°)] + \\ &\quad [v_B \times i_{RB} \times t \times \cos(60° - 45°)] \\ &= (v_R \times i_{RB} \times t \times \cos 105°) + \\ &\quad (v_B \times i_{RB} \times t \times \cos 15°) \end{aligned}$$

With balanced voltages this becomes:

$$\begin{aligned} W_1 + W_2 &= [v \times i \times t \times (-0{\cdot}259)] + [v \times i \times t \times 0{\cdot}966] \\ &= v \times i \times t \times 0{\cdot}707 \end{aligned}$$

Thus the sum of the energy registered by the two meter elements is equal to the energy expended in the load.

It may be noted that cos 105 deg. is a minus quantity (−0·259), indicating that with current displaced 105 deg. behind the voltage the direction of rotation of the disc in the meter element M_R will be reversed. This is shown in Fig. 93 where the current vector i_{RB2} is displaced 45 deg. + 60 deg. behind the voltage vector v_R. Reversal takes place when the current is displaced more than 90 deg. behind the voltage in the meter element, that is, when the current i_{RB} in the load circuit lags more than 45 deg. behind the applied voltage V_{RB} corresponding to a power-factor lower than 0·707.

The foregoing explanations concern the behaviour of two separate single-phase meters measuring the energy consumption in a two-

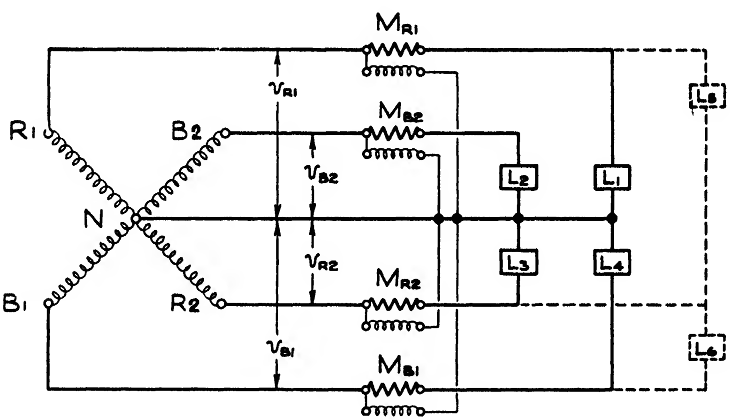


FIG. 94.—Measurement of energy in a two-phase five-wire circuit.

phase three-wire circuit. If a two-element polyphase meter is used instead of two single-phase meters each element will tend to register at the same rate as a separate single-phase meter, and the rotor will rotate at a speed proportional to the sum of the two separate registrations. With a load L_3 connected between the lines R B as in Fig. 92, each element will drive in the forward direction so long as the power-factor of this load is higher than 0·707, but for lagging power-factors below this value, the element in the red line will tend to register in the reverse direction. This tendency will always be less than the tendency of the element in the blue line to register in the forward direction and the net result will be a forward registration of the correct quantity, proportional to the difference between the forward and reverse torques acting on the rotor.

Because of the possibility of registration occurring in the reverse direction when single-phase meters are used, a polyphase meter should be installed where a load is connected between the lines R B. This avoids the raising of doubts in the minds of non-technical consumers who may suspect that the metering arrangements are inaccurate if one meter is observed to register in the forward direction under some conditions and backwards under others. Needless to say, the single-phase method is correct, despite reversal under low power-factor conditions. In the case of a load having a leading power-factor the meter element in the blue line will register the slower as the power-factor becomes less and will reverse or tend to reverse when the power-factor falls below 0·707. Where a single-phase load is connected between the lines R B only, as at L_3 in Fig. 92 and there is no connection to the neutral, one single-phase meter should be used instead of two; the current coil would be connected in either the red or the blue line, with the voltage coil across the lines. The meter would of course be so situated as to exclude any current passing through loads such as L_1 or L_2 and reverse rotation could not occur at any power-factor.

7.5. Measurement of Energy in Two-Phase Five-Wire Systems. The method of measuring energy consumption in a two-phase five-wire system is an extension of the method adopted when dealing with two-phase three-wire supplies as the same principles are involved. Four single-phase meters may be used as indicated in Fig. 94 at M_{R1} M_{B2} M_{R2} M_{B1}*. Each meter has a current coil connected in one of the lines and a voltage coil connected between the same line and the neutral. The loads may be connected between lines and neutral as at L_1 L_2 L_3 L_4, across one phase as at L_5, or across two phases as at L_6. This system of distribution lends itself to a multitude of methods of loading, but whatever method is adopted, four meters arranged as shown will correctly register the total consumption under all conditions.

Assuming balanced load conditions, the total expenditure of energy in four loads such as L_1 L_2 L_3 L_4 will be:

$$W = 4\,(v \times i \times t \times \cos\phi)$$

w ere W is the total consumption in watt-hours
v is the voltage between any line and neutral
i is the current taken by each load
t is the time in hours and
$\cos\phi$ is the power-factor of each load.

* See also page 242 dealing with two-phase five-wire meters for balanced voltages.

Similarly, four loads connected, each across two phases as at L_6 would register:

$$W = 4\,(V \times i \times t \times \cos\phi)$$

where V is equal to $\sqrt{2} \times v$ and is the voltage between any pair of red and blue lines. Finally, two loads connected across the outer conductors of each phase as at L_5 would register:

$$W = 2\,(2v \times i \times t \times \cos\phi)$$

Instead of using four single-phase meters for measuring the total consumption, two two-element polyphase meters may be used or alternatively one four-element polyphase meter. This latter is not made on a commercial scale in this country, and in countries where two-phase five-wire distribution is common, two-element balanced voltage meters

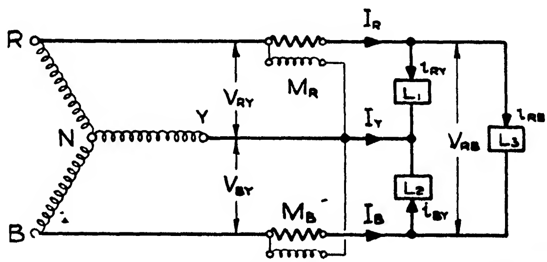


FIG. 95.—Measurement of energy in a three-phase three-wire circuit.

are employed in most cases. Although these last mentioned meters are not as accurate under certain conditions the method appears to be acceptable to all concerned with their use. The possibilities of error are usually comparatively small and in favour of the consumer, and presumably the supply authorities are prepared to accept the possibility rather than incur the additional costs of four-element meters. Reference to meters suitable for balanced voltages is made later in this chapter.

7.6. Measurement of Energy in Three-Phase Three-Wire Systems. The energy in a three-phase three-wire system can be measured by means of two single-phase meters or one two-element polyphase meter, connected as shown in Fig. 95. This diagram may be compared with the diagram for a two-phase, three-wire meter in Fig. 92 as the conditions are similar in many respects. The meter M_R has its current coil connected in the red line and its voltage coil between the red and yellow.

The meter M_B has its current coil connected in the blue line and its voltage coil between the blue and yellow. The total load consists of three separate single-phase loads which may be connected either in star or in delta. The diagram shows the loads connected in delta. The energy expended in each load is as follows:—

$$\begin{aligned} \text{Energy in } L_1 &= W_1 = V_{RY} \times i_{RY} \times t \times \cos \phi_{RY} \\ L_2 &= W_2 = V_{BY} \times i_{BY} \times t \times \cos \phi_{BY} \\ L_3 &= W_3 = V_{RB} \times i_{RB} \times t \times \cos \phi_{RB} \end{aligned}$$

The terms ϕ_{RY} ϕ_{BY} ϕ_{RB} in these expressions refer to the phase difference between voltage and current in the load with which they are associated.

As regards the energy expended in the load L_1 this is measured by the meter element M_R, and when the load is non-inductive, the current i_{RY} passing through the current coil of the meter element will be in phase with the voltage V_{RY} across the terminals of the meter voltage coil. At any other power-factor the phase difference between current and voltage will be the same in the coils of the meter as in the load circuit. Similar conditions exist in the case of the load L_2 in relation to the meter element M_B. Thus, the loads L_1 L_2 may be regarded as two independent single-phase loads being metered by two independent single-phase meters.

The conditions as regards the energy expended in the load L_3 are somewhat different. The current i_{RB} passes through the current coils of both meters, in the forward direction through M_R and the reverse direction through M_B. When the load is non-inductive, the current i_{RB} which is in phase with the voltage V_{RB}, will be lagging 60 deg. with respect to the voltage V_{RY} in the meter element M_R and leading 60 deg. with respect to the voltage V_{BY} in the meter element M_B. Thus, the power-factor at which the meter elements are operating if the load L_3 is the only load on the system will be equal to cos 60 deg., i.e. 0·5 lagging in the meter element M_R and 0·5 leading in the element M_B. This condition is shown by the vector diagram in Fig. 96 where the current vector i_{RB}, in phase with the voltage V_{RB}, is lagging 60 deg. behind the voltage V_{RY}, and the vector $-i_{RB}$ in phase opposition to V_{RB} is leading 60 deg. in front of the voltage V_{BY}. The minus sign in the quantity $-i_{RB}$ indicates that this current is reversed in direction in the meter element M_B.

At any power-factor other than unity the current i_{RB} will lag by an angle ϕ, as indicated by the vectors i_{RB1} and $-i_{RB1}$. The phase difference between current and voltage will then become 60 deg. $+ \phi$ in the

element M_R and $\phi - 60$ deg. in the element M_B. The minus sign in -60 deg. indicates that this is a leading phase angle. It will be obvious that as the power-factor of the load L_3 becomes less than unity the phase difference between current and voltage in the meter element M_R will increase and in the element M_B will become less, until, with a power factor of 0·5 (60 deg. lag), the current and voltage will be in phase in the element M_B. Beyond this point the current will lag with respect to the voltage in both meters.

Consideration may now be given to the amount of energy registered by each meter element. Assuming balanced loads and unity power-

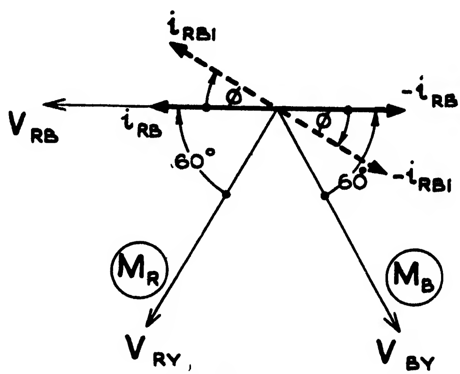


FIG. 96.—Vector diagram showing single-phase load on three-phase three-wire circuit.

factor the element M_R will register the consumption in L_1 and part of L_3, while the element M_B will register the consumption in L_2 and part of L_3. Let W_R represent the energy registered by M_R and W_B the energy registered by M_B. Then the total registration will be:

$$W = W_R + W_B.$$

The quantity registered by each at unity power-factor is:

$$W_R = (V_{RY} \times i_{RY} \times t) + (V_{RY} \times i_{RB} \times t \times \cos 60°)$$
$$W_B = (V_{BY} \times i_{BY} \times t) + (V_{BY} \times i_{RB} \times t \times \cos -60°)$$

The first bracketed term in each of these expressions is the registration due to the energy expended in the loads L_1 and L_2 respectively; the second bracketed term in each expression is due to the energy expended in the load L_3. Since the loads are assumed to be balanced,

the voltages and currents are the same in each expression which can be restated as follows:

$$W_R = (V \times i \times t) + (V \times i \times t \times 0{\cdot}5) = 1{\cdot}5\,(V \times i \times t)$$
$$W_B = (V \times i \times t) + (V \times i \times t \times 0{\cdot}5) = 1{\cdot}5\,(V \times i \times t)$$

It is obvious from the foregoing that each meter element is registering the same amount and that the total energy measured by the two elements is:

$$W = W_R + W_B = 1{\cdot}5\,(V \times i \times t) + 1{\cdot}5\,(V \times i \times t)$$
$$= 3\,(V \times i \times t)$$

The current I in each line is $\sqrt{3}$ times the current i in each arm of the delta-connected load, i.e. $i = I/\sqrt{3}$. Substituting this value, we may express the total energy registered by the two meter elements in terms of line voltage and current as:

$$W = 3\,(V \times i \times t) = 3\,(V \times I/\sqrt{3} \times t) = \sqrt{3} \times V \times I \times t$$

At any power-factor other than unity the amounts registered by the two meter elements will differ. With a lagging power-factor the registration on the element M_R will decrease, and on M_B will increase. Assuming that the current lags in each load by an angle ϕ, and that the loads are still balanced, then:

$$W_R = [V \times i \times t \times \cos\phi] + [V \times i \times t \times \cos(60° + \phi)]$$
$$W_B = [V \times i \times t \times \cos\phi] + [V \times i \times t \times \cos(\phi - 60°)]$$

The amounts registered by the two meter elements due to the loads L_1 and L_2 are alike, and the difference in registration is due to the load L_3. This difference will be seen in Fig. 96 where the vector i_{RB1} represents the current in the meter element M_R, lagging by 60 deg. $+\ \phi$ behind the voltage vector V_{RY}, and the vector $-i_{RB1}$ represents the current in the meter element M_B, lagging by ϕ − 60 deg. behind the voltage vector V_{BY}. If a numerical value is assigned to ϕ, say 30 deg., then the current in the element M_R will be lagging by $60° + 30° = 90°$ and the energy registered by the element M_R due to the load L_3 will be:

$$W_R = V \times i \times t \times \cos 90°$$

As cos 90 deg. = zero, the energy registered will also be zero. The current in the element M_B will be lagging by $30° - 60° = -30°$ and the energy registered by the element due to the load L_3 will be:

$$W_B = V \times i \times t \times \cos -30°$$

The numerical value of cos 30 deg. and cos — 30 deg. is 0·866, the minus sign indicating that the current in this case is leading. The registration on the two elements has now become:

$$W_R = (V \times i \times t \times 0{\cdot}866) + \text{zero}$$
$$W_B = (V \times i \times t \times 0{\cdot}866) + (V \times i \times t \times 0{\cdot}866)$$

Each of these expressions in brackets represents the energy expended in one load and all are alike since the loads are balanced. The total registration by the two meter elements when the current lags 30 deg., corresponding to a power-factor of 0·866 is therefore:

$$W = W_R + W_B = 3\,(V \times i \times t \times 0.866)$$

Expressed in terms of line voltage and current at any power-factor this becomes:

$$W = 3\,(V \times I/\sqrt{3} \times t \times \cos\phi)$$
$$= \sqrt{3} \times V \times I \times t \times \cos\phi$$

Without further explanation it will be clear that, should the current lag by more than 30 deg. the registration on the meter element M_R due to the energy expended in L_3 will be a minus quantity, that is to say, the element will tend to reverse in direction and will in fact do so if the load L_1 is switched off. The rate of registration on the meter element M_B, on the other hand, will increase as the current lags more and more, until the angle of lag is 60 deg. corresponding to a power-factor of 0·5. At this point the current vector $-i_{RB1}$ will coincide with the voltage vector V_{BY}, and the meter element M_B will be operating at unity power-factor.

It is unusual in practice for the energy consumption in a three-phase three-wire circuit to be measured by means of two single-phase meters. Instead, a two-element polyphase meter is used, in which case the registration will always be in the forward direction. The tendency for one element to reverse will be less than the tendency for the other element to run forwards and the total registration will be proportional to the algebraic sum of the torques on the two elements.

To summarize the foregoing it may be stated that where the meter elements are connected in the red and blue lines respectively, as is usual, variations in the load connected between the red and yellow lines will affect the registration of the red element only, and variations in the load connected between the blue and yellow lines will affect the registration of the blue element only. The load connected between the

red and blue lines will affect the registration of both elements, by an amount depending upon the power-factor. If the power-factor is unity both elements will share the registration equally, but if less than unity the blue element will register an increasing share until, with a power-factor (lagging) of 0·5, the red element will cease to register. Below this power-factor the red element will reverse, or tend to reverse, and thus will cancel part of the registration on the blue element. Conversely, a

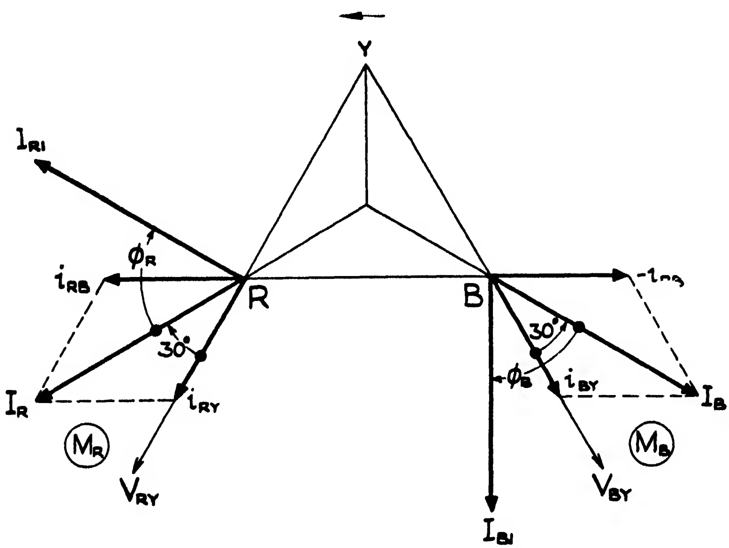


FIG. 97.—Phase relationships in meter elements due to three-phase load on three-phase three-wire circuit.

leading power-factor will result in the red element taking an increasing share of the registration.

The vector diagram in Fig. 96 refers only to the conditions arising from a single-phase load connected between the red and blue lines, and from the explanation already given at length it will be obvious that a two-element polyphase meter is capable of registering accurately under extreme conditions of unbalanced load, such as a single-phase load connected between any pair of lines. Such extreme conditions of unbalance are unusual on a three-phase three-wire circuit, the more usual condition being for load to be connected between all three lines. It will also be obvious that with a distributed load each meter element can register simultaneously the current due to loads on two separate

phases, such registrations being additive or subtractive according to the power-factor of the loads in question.

The effect on the two meter elements of the loads L_1 L_2 L_3 in Fig. 95 acting simultaneously is shown in the vector diagram in Fig. 97. The loads are assumed to be balanced and non-inductive. The vectors i_{RY} and i_{RB} represent the phase of the currents relative to the phase of the voltage V_{RY} in the meter element M_R. The current vector I_R which is the resultant of the currents i_{RY} and i_{RB}, is lagging 30 deg. behind the voltage vector V_{RY} under this condition, that is, when the power-factor of the load is unity. Similarly in the meter element M_B, the current vector I_B, which is the resultant of the current vectors i_{BY} and $-i_{RB}$, is leading 30 deg. in front of the voltage vector V_{BY} when the power-factor of the load is unity.

At any other power factor, when the current is lagging by an angle ϕ, the resultant current is represented by the vector I_{R1} lagging by an angle ϕ_R in the element M_R, and by the vector I_{B1} lagging by an angle ϕ_B in the element M_B. It will now be seen that when the load is inductive the resultant current I_{R1} in the element M_R is lagging by an angle $\phi_R +$ 30 deg., and the resultant current I_{B1} in the element M_B is lagging by an angle of $\phi_B - 30$ deg.

The energy registered by the two meter elements M_R and M_B is W_R and W_B respectively, and the total energy W is equal to $W_R + W_B$; from the geometry of Fig. 97 it will be seen that, at unity power-factor, this is proportional to:

$$\begin{aligned} W = W_R + W_B &= (V_{RY} \times I_R \times t \times \cos 30°) + (V_{BY} \times I_B \times t \times \cos -30°) \\ &= (V_{RY} \times I_R \times t \times 0{\cdot}866) + (V_{BY} \times I_B \times t \times 0{\cdot}866) \end{aligned}$$

Where the load is balanced, this becomes:

$$\begin{aligned} W = W_R + W_B &= (V \times I \times t \times 0{\cdot}866) + (V \times I \times t \times 0{\cdot}866) \\ &= 2\,(V \times I \times t \times 0{\cdot}866) \\ &= \sqrt{3} \times V \times I \times t \end{aligned}$$

and at any power-factor other than unity the total energy registered is:

$$W = \sqrt{3} \times V \times I \times t \times \cos \phi$$

The foregoing remarks have reference to a three-phase three-wire load, connected in delta, but would apply equally well to a star-connected load if current values are expressed in terms of line currents; they would not apply in the case of a star-connected unbalanced load where the star point is connected to the neutral of the supply system.

For such a case three meter elements are necessary to obtain correct registration.

7.7. Measurement of Energy in Three-Phase Four-Wire Systems. The measurement of energy in a three-phase four-wire circuit may be effected by means of three single-phase meters or one three-element polyphase meter. The latter is the more usual as a matter of convenience, since the space occupied by one polyphase meter is less than that required for three single-phase meters and the connections are simpler. Nevertheless, a few supply authorities prefer to use three single-phase meters in order to ascertain whether the load is distributed more or less equally over the three phases. As shown in the connection diagram in Fig. 98, each meter element has a current coil connected in one line and a voltage coil connected between the same line and the neutral.

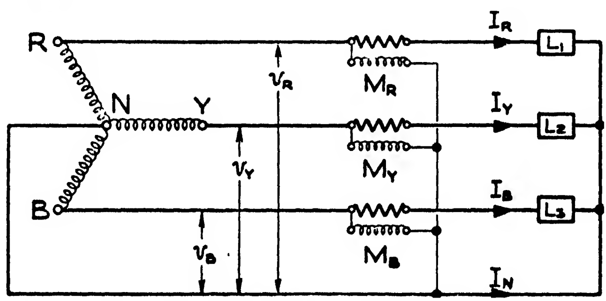


FIG. 98.—Measurement of energy in three-phase four-wire circuit.

The three-phase load consists of three single-phase loads connected in star and represented by L_1 L_2 L_3. With this arrangement of connections each meter element measures the energy consumption in one single-phase load only and is not influenced by the load conditions in the phases to which it is not connected.

The energy registered by the three meter elements M_R M_Y M_B is denoted by W_R W_Y W_B respectively, corresponding to the energy consumption in the loads L_1 L_2 L_3. If the voltages between lines and neutral are denoted by v_R v_Y v_B, the line currents by I_R I_Y I_B, and the phase displacements between voltage and current in each load by ϕ_R ϕ_Y ϕ_B respectively, then the energy registered by each meter element during a time interval t will be:

Energy registered by $M_R = W_R = v_R \times I_R \times t \times \cos\phi_R$

" " " $M_Y = W_Y = v_Y \times I_Y \times t \times \cos\phi_Y$

" " " $M_B = W_B = v_B \times I_B \times t \times \cos\phi_B$

A vector diagram illustrating the phase relationship between current and voltage in the three meter elements and also in the three load circuits, when the load is inductive and approximately balanced, is shown in Fig. 99.

The total energy W registered by the three elements is:

$$W = W_R + W_Y + W_B$$

and if the loads are balanced and the power-factor of each is the same, this becomes:

$$W = 3\,(v \times I \times t \times \cos\phi)$$

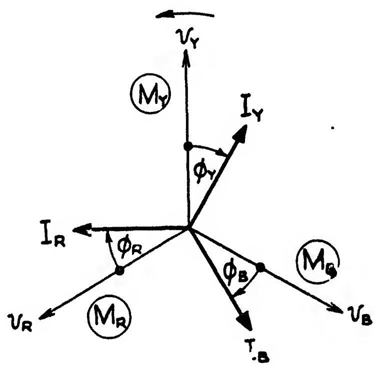


FIG. 99.—Phase relationships in meter elements due to three-phase four-wire inductive load.

But $v = V/\sqrt{3}$ and substituting this value we have:

$$\begin{aligned} W &= 3\,(V/\sqrt{3} \times I \times t \times \cos\phi) \\ &= \sqrt{3} \times V \times I \times t \times \cos\phi \end{aligned}$$

This value is the same as that obtained in the case of a three-phase three-wire meter.

It may be observed that with a star-connected load the phase displacement between voltage and current in each meter element is the same as in the load to which it is connected. When the load is balanced in all respects there is no current in the neutral conductor and the behaviour of the three meter elements is exactly the same as if the load were delta connected and balanced. It is in fact immaterial whether the load is star or delta connected, or a mixture of both, as the meter will register correctly under any condition of loading, balanced or unbalanced.

A single-phase load connected between any pair of lines will be registered on two meter elements. In view of the full explanation given in the case of a three-phase three-wire meter, it will be appreciated that such a load will cause the registration on the two meter elements to be shared equally when the power-factor of the load is unity, and unequally at any other power-factor. It will also be obvious that, with unity power-factor in the load circuit, there will be a phase difference of 30 deg. between current voltage in each meter element, the current leading in the one, and lagging in the other.

7.8. Balanced-Load Meters for the Measurement of Energy. The methods already described for the measurement of energy in polyphase circuits are accurate, whether the loads on the separate phases are balanced or unbalanced. Where a supply of power is provided by a supply undertaking the consumer has a right to expect that all reasonable precautions will be taken to ensure the accuracy of the meter installed on his premises. In the absence of any special agreement to the contrary, between the supply authority and the consumer, the meter must be of an approved pattern and certified by the Ministry of Fuel and Power. Only meters which are correct on balanced and unbalanced loads may be certified and consequently unbalanced load meters are invariably used by supply undertakings. At the same time, balanced-load meters which are less costly, fulfil all essential requirements in certain cases and their use may be justified where the meter registration does not form the basis for revenue purposes. For example, balanced-load meters may be used in factories and other situations where it is desired to keep an account of energy consumed in separate departments, either for record purposes or in order to arrive at the approximate cost of energy expended in manufacturing processes; also, for comparing the cost of operating one machine as against another, the use of balanced-load meters may be justified and provided that the load is actually balanced, the results may be just as accurate as if an unbalanced load meter had been used.

7.9. Two-Phase Three-Wire Balanced-Load Meter. The simplest form of balanced-load meter is a single-phase meter connected in one phase of a polyphase circuit. Take for example, the two-phase three-wire circuit shown in Fig. 92 in which two single-phase meters or one two-element polyphase meter are installed. If the load consists simply of two single-phase loads as represented by L_1 L_2 and these loads are balanced, then in the case of the two separate meters the registration of the one will be the same as that of the other. Obviously then, it is

not necessary to install two meters which register alike and one meter may be dispensed with. The registration on the remaining meter must then be multiplied by two and this may be done after taking the meter reading, or preferably the gearing in the register may be arranged to give a direct reading without applying a multiplying factor. It is usually safe to assume that the load is reasonably balanced if it consists simply of motors, but it is very unlikely that a lighting load will be balanced or will remain balanced. The assumption is also made that the voltage on each phase is the same. A balanced-load meter should not be used if any part of the load is connected across the outers of a two-phase three-wire system, such as the load L_3 in Fig. 92. It has already been explained that if the power-factor of the load L_3 departs from unity the registrations on the two meters represented by M_R M_B will be unequal, and to apply a multiplying factor to either would obviously be misleading.

7.10. Two-Phase Four-Wire and Five-Wire Balanced-Load Meter. A single-phase meter can be used as a balanced-load meter in a two-phase four-wire circuit as shown in Fig 91 provided that the conditions already stated as necessary are observed. It is very unlikely however, that a balanced-load meter would be satisfactory in the two-phase five-wire circuit shown in Fig. 94. Too many opportunities exist for the connection of one or more single-phase loads across the outers of the system, which would completely upset the accuracy of the indications of a single-phase meter connected as at M_{R1} M_{R2} M_{B1} or M_{B2}. If however, it can be ensured that the load is truly balanced and is likely to remain so, then a single-phase meter with a multiplying-factor of four can be used in a five-wire circuit. For the two-phase four-wire balanced-load meter, the multiplying-factor would of course be two,

7.11. Three-Phase Four-Wire Balanced-Load Meter. The example of the use of a single-phase meter most frequently met, for metering a balanced polyphase load, is in connection with a three-phase four-wire system as depicted in Fig. 98. Here, if the loads L_1 L_2 L_3 are truly balanced, a single-phase meter connected as at M_R M_Y or M_B may be used and a multiplying factor of three applied to the registration on the register. In common with several of the examples already given, this balanced-load meter is used on a polyphase system having a neutral conductor. The current coil of the meter is connected in one of the lines and the voltage coil between the same line and the neutral. The registration of the meter is then multiplied by the number of lines in

the system, excluding the neutral; this principle can be adopted for a polyphase system of any number of phases.

7.12. Three-Phase Three-Wire Balanced-Load Meter. Where the neutral conductor is not available, as in a three-phase three-wire system, a single-phase meter is frequently used, having two windings

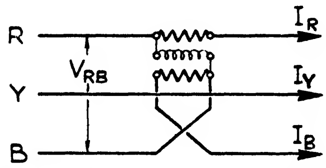


FIG. 100.—Three-phase three-wire balanced-load meter with two current coils.

on the current electromagnet. These windings are connected in two of the lines and the voltage coil is connected across the same two lines as shown in Fig. 100. It will be observed that the current winding in line *B* is reversed relative to the winding in line *R*, the effect of which is

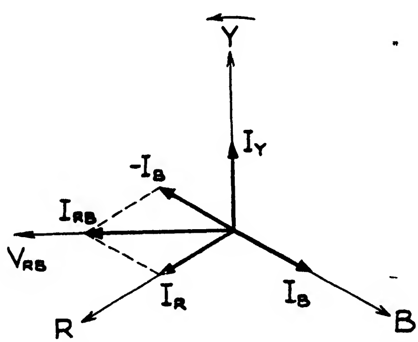


FIG. 101.—Vector diagram for three-phase three-wire balanced-load meter.

to produce a flux in the current electromagnet in phase with the voltage across the lines *R B* when the load is non-inductive.

The vector diagram in Fig. 101 shows the phase relationship between current and voltage in the meter windings; the vector V_{RB} is in phase with the voltage across the lines *R B* to which the voltage coil is connected. The currents in lines *R* and *B* are represented by the vectors I_R I_B, and as the current winding in line *B* is reversed the vector $-I_B$

indicates the effect of this reversal. The equivalent current vector I_{RB} is the resultant of the vectors I_R and $-I_B$ and is in phase with the voltage vector V_{RB} when the load is balanced and the power-factor is unity. If the load is inductive, the current vectors will be displaced in a clockwise direction relative to the positions shown in the diagram.

The meter functions just like an ordinary single-phase meter and can be tested as such by connecting the two current coils in series. Under this condition it will register at a rate proportional to $2 \times V \times I \times t \times \cos\phi$, that is, twice the single-phase load. When operating on a three-phase circuit however, the currents represented by the vectors I_R and $-I_B$ will be displaced in phase by 30 deg. from the voltage V_{RB} when the power-factor is unity, leading in the one case and lagging in the other. Accordingly, at unity power-factor, the registration will be at a rate proportional to $2 \times V \times I \times t \times \cos 30°$ or $\sqrt{3} \times V \times I \times t$ which is correct for a three-phase balanced load.

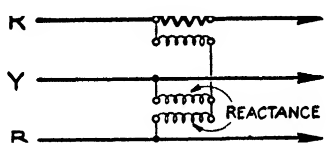


FIG. 102.—Three-phase three-wire balanced-load meter with artificial neutral.

When the current to be metered exceeds fifty amperes it is usual to provide two current transformers, the secondary windings of which may be connected to the two meter current coils. A simplification can be effected by using an ordinary single-phase meter, having a 10-ampere current coil, and connecting the two transformer secondaries in parallel; the secondary of the transformer in line B is connected in reverse and the vector sum of the two currents produces the same result in the meter current coil as would be produced if the two currents were fed in separately through two current coils. A balanced-load meter of this type registers at a rate proportional to $\sqrt{3} \times V \times I \times t \times \cos\phi$ provided that the current, voltage, and power-factor are the same in each phase of the load.

An alternative method of metering a three-phase three-wire balanced load which is sometimes employed is shown in Fig. 102. The meter has a current coil connected in line R and a voltage coil connected between the same line and an artificial neutral point created at

the junction of two reactances, the free ends of which are connected to lines Y and B respectively. Usually the reactances consist of two voltage electromagnets identical with that used in the meter itself, and provided that the impedance of each of the three electromagnets is the same the artificial neutral created will be at the same potential as the neutral of the supply system. In this case the voltage across the meter voltage coil will be in phase with the current in line R when the load is non-inductive and balanced, and the magnitude of the voltage will be the same as the voltage between line and neutral of the supply. The meter will register the quantity $3 \times v \times I \times t \times \cos\phi$ when the load is truly balanced and this is equal to $\sqrt{3} \times V \times I \times t \times \cos\phi$. Where large currents are being metered, which involve the use of current transformers, this method has a slight advantage over that described in the previous paragraph, in that it permits one of the two current transformers to be omitted.

When a balanced-load meter of this type is used on a high voltage system, and a three-phase voltage transformer is installed for some other purpose, the reactances used for creating an artificial neutral are unnecessary if the voltage transformer secondaries are star connected; in this case a neutral point already exists on the voltage transformer and can be utilized in place of the artificial neutral. The difference between the cost of a balanced-load meter and a meter which is correct on unbalanced loads is frequently very small and in view of the limitations of balanced-load meters the practice of using them in such cases is to be deprecated.

7.13. Two-Phase Five-Wire Meter for Balanced Voltage. There is another class of balanced-load meter which is normally accurate on unbalanced loads, provided that the voltages are balanced. Strictly speaking, this class might be described as including meters for balanced voltage. The first to be described is used on two-phase five-wire systems and is shown in Fig. 103. It consists of a two-element polyphase meter, each element comprising a voltage coil and two current coils. The element M_B has a current coil in each of the lines B_1 B_2 and a voltage coil connected between these lines. Similarly the element M_R has a current coil in each of the lines R_1 R_2 and a voltage coil connected between the same lines. A numerical example may be considered to show the effect of unbalanced voltage on one element of the meter, the other element being similarly affected.

Let it be assumed that the voltages v_{B1} and v_{B2} are balanced and that each is equal to 100 volts. Then the voltage V_B will be 200 volts.

The meter element M_B will register at a rate proportional to the total power in watts expended in the circuit, that is:

$2 \times v \times I$ if one assumes the power-factor to be unity.

If the current in each line B_1 B_2 is 10 amperes the rate of registration will be proportional to:

$$2 \times 100 \text{ volts} \times 10 \text{ amperes} = 2{,}000 \text{ watts},$$

and each current coil will contribute half this amount; if now the load in line B_1 be disconnected the rate of registration will be reduced to one half the previous amount.

Now let the voltage v_{B1} be reduced to 90 volts and v_{B2} be raised to

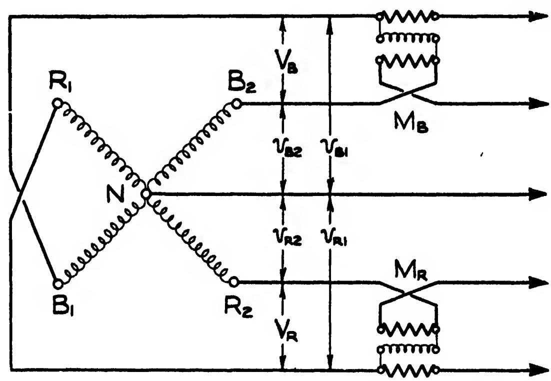


FIG. 103.—Two-phase five-wire meter for balanced voltage.

110 volts, the current in line B_2 being readjusted to 10 amperes; the rate of registration will still be one half the original rate as the voltage across the terminals of the voltage coil is still 200 volts. But the load has been reduced to 90 volts $\times$ 10 amperes = 900 watts, consequently the rate at which the meter is registering is too much by 100 watts. A little consideration will show that with current in one line maintained at a constant value, the voltage between line and neutral may be varied up or down to any extent without affecting the rate of the meter, provided that the voltage V_B which is the sum of the voltages v_{B1} and v_{B2} remains unaltered.

Where two-phase five-wire supplies are in use, two-element polyphase meters of this type are used for the metering of these supplies. Although this two-element meter is subject to error when the voltage

is unbalanced, the presumption is that the error is not regarded as serious under working conditions, or alternatively the extent of the voltage unbalance is maintained within such small limits that the actual error is of negligible importance.

7.14. Three-Phase Four-Wire Meter for Balanced Voltage. A three-phase four-wire meter for use on unbalanced loads where the voltages are balanced is shown in Fig. 104. This meter has been used extensively in the past and many are still in use, but as a type it is not approved by the Ministry of Fuel and Power and consequently it is not certifiable. In construction it is similar to the two-phase five-wire meter shown in Fig. 103 in that it has two elements each comprising a voltage coil associated with two current coils. It differs from the two-phase meter

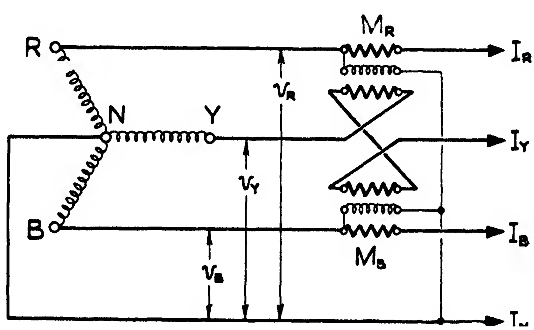


FIG. 104.—Three-phase four-wire meter for balanced voltage.

in that a current coil in one element is connected in series with a current coil in the other element; also, one end of each voltage coil is connected to the neutral conductor. Referring to Fig. 104, the two elements of the meter are represented by M_R M_B. A current coil in the red line is associated with a voltage coil connected between red and neutral; a current coil in the blue line is associated with a voltage coil connected between blue and neutral. There are two current coils in the yellow line, one on the same electromagnet as the red current coil and the other on the same electromagnet as the blue current coil; both yellow current coils are reversed.

The phase relationships between current and voltage in the various circuits, on a non-inductive load, are shown in the vector diagram in Fig. 105. In the red element M_R, the red current I_R is in phase with the voltage v_R between line and neutral, and the yellow current $-I_Y$ is

leading the voltage by 60 deg. In the blue element M_B, the blue current is in phase with the voltage v_B between line and neutral and the yellow current $-I_Y$ is lagging behind the voltage by 60 deg. The minus sign preceding $-I_Y$ indicates that this vector is reversed. The energy registered by the two elements of the meter may be represented by W_R for the red element and W_B for the blue element. The total energy $W = W_R + W_B$. It will be seen from the diagram that when the power-factor is unity

$$W_R = (v_R \times I_R \times t) + (v_R \times I_Y \times t \times \cos -60°)$$

and

$$W_B = (v_B \times I_B \times t) + (v_B \times I_Y \times t \times \cos 60°)$$

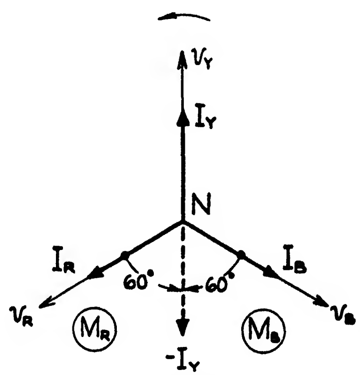


FIG. 105.—Vector diagram for three-phase four-wire meter on non-inductive load.

where t is the time during which the load is maintained. The minus sign in cos $-$ 60 deg. indicates that the current is leading the voltage. The numerical value of cos $-$ 60 deg. is the same as cos 60 deg.

If the voltages are balanced, then

$$v_R = v_Y = v_B = v$$

Accordingly we may write:

$$W_R = (v \times I_R \times t) + (v \times I_Y \times t \times \cos -60°)$$

and

$$W_B = (v \times I_B \times t) + (v \times I_Y \times t \times \cos 60°)$$

and since cos $-$ 60 deg. = cos 60 deg. we may also write:

$$W = (v \times I_R \times t) + (v \times I_B \times t) + 2\,(v \times I_Y \times t \times \cos 60°)$$

The expression $2\,(v \times I_Y \times t \times \cos 60°)$ is the energy expended in the

yellow phase which is registered jointly by the two meter elements, and as cos 60 deg. = 0·5 this value may be substituted and we may write:

$$2\,(v \times I_Y \times t \times 0{\cdot}5) = v \times I_Y \times t$$

The total energy registered by the meter on a non-inductive load therefore becomes:

$$W = (v \times I_R \times t) + (v \times I_Y \times t) + (v \times I_B \times t)$$

When the load is inductive, and assuming that the power-factor is the same in each phase, the current vectors will be displaced in a clockwise direction by an angle ϕ; the effect of this in the yellow phase is to displace the vector $-I_Y$ in the direction of I_R and away from I_B. The expressions for the energy measured by each element with balanced voltages now become:

$$W_R = (v \times I_R \times t \times \cos\phi) + [v \times I_Y \times t \times \cos(-60° + \phi)]$$
and $$W_B = (v \times I_B \times t \times \cos\phi) + [v \times I_Y \times t \times \cos(60° + \phi)]$$

The expressions in square brackets represent the energy in the yellow phase. It will be seen that as the power-factor departs from unity and the load becomes inductive the proportion of the energy in the yellow phase which is registered on the red element of the meter tends to increase, and the proportion registered on the blue element tends to decrease. When ϕ becomes 30 deg. there will be no registration on the blue element due to the yellow current; this follows because the value of the term cos (60 deg. + 30 deg.) i.e. cos 90 deg., is equal to zero, and the whole of the expression in square brackets is therefore equal to zero. If ϕ exceeds 30 deg., there will be developed a reverse torque, which will tend to oppose the forward registration on the blue element.

The two-element three-phase four-wire meter just described can only be constructed satisfactorily for comparatively small current ratings. Current ratings of 25 amperes and upwards present difficulties in manufacture and test, and the performance is not all that might be desired. The difficulties arise mainly because it is not possible to adjust the individual driving torques produced by two current coils on one electromagnet. The inherent driving torques resulting from each current winding are approximately correct, but any error which does exist cannot be rectified by adjustment; also mutual interference due to leakage fluxes from the current windings are difficult to eliminate. These sources of error are small in the low-current ratings, but increase rapidly in the higher ratings. For currents in excess of 50 amperes

current transformers are required, and consequently a meter having three current windings of 5-ampere rating may be used. This disposes of some of the errors referred to above, and the arrangement is satisfactory subject to the limitations which are inherent to this type of meter.

An alternative which is frequently adopted in transformer-operated meters is to employ a 10-ampere meter having two current windings only, and to connect the current transformer secondaries in delta as shown in Fig. 106. The effect of this method of connection is the same as if the meter had three current windings and it avoids error due to lack

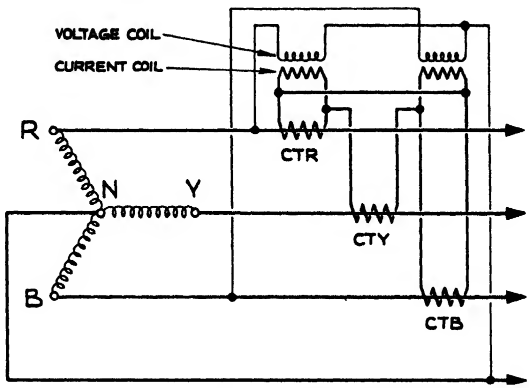


FIG. 106.—Three-phase four-wire two-element meter with delta-connected current transformers.

of balance between current windings on the same electromagnet. The current transformers *CTR CTB* feed into the current windings of the meter elements M_R M_B respectively. The current transformer *CTY* feeds from its left-hand secondary terminal through the current winding of M_R in the reverse direction, then along the interconnecting wire and through the current winding of M_B, also in the reverse direction back to the right-hand terminal of the secondary. The nett result is that each meter current winding carries the vector difference of two currents displaced 120 deg. apart; the result is precisely the same as that produced by two current windings per element shown in Fig. 105.

7.15. Factors Limiting the Accuracy of Polyphase Meters. The performance of a polyphase meter is fundamentally the same as that of the single-phase elements from which it is built up. There are however, certain disturbing factors present in a polyphase meter which are absent

in its single-phase counterpart and which tend to make its inherent errors greater. A polyphase meter consists of two or more driving elements acting upon a common rotor, which latter may be provided with one, two, or three discs, and one or more braking magnets. The magnetic fields set up in each driving element produce leakage fluxes which penetrate into the space occupied by adjacent elements and, according to the intensity and phase relationship of the leakage flux, tend to modify the performance of the adjacent element in question. Currents induced in the rotor disc by one driving element may stray into the area influenced by another element, causing undesirable errors to appear. In order that a polyphase meter may register correctly when the load is unbalanced, it is essential that each element of the meter registers the same amount, when a load of a given magnitude is connected to the element under consideration. The phase sequence is important when dealing with polyphase meters; it is probably true to say that every polyphase meter is influenced to some extent by reversal of phase sequence, although the change in the error is remarkably small in some instances. The standard phase sequence adopted in Britain for three-phase supplies, is red–yellow–blue, that is, the pressure rises to a maximum in the phases in that sequence.

Since single-phase meters are immune from the additional errors referred to above, a few supply authorities prefer to use two or three single-phase meters instead of one polyphase meter, in order to obtain more accurate registration. This procedure is more costly and also inconvenient since the space occupied is greater, the amount of connecting-up is increased, and two or three meters as the case may be, have to be read instead of one. The method cannot be adopted where a measurement of maximum demand is necessary, since two or three demand indicators would have to be installed and the sum of the demand registrations would not give the correct summated demand. On the other hand, where check metering is necessary on important bulk supplies, single-phase check meters may be preferable if the disadvantages above mentioned are relatively unimportant, and their use in some cases enables information to be obtained concerning the average power-factor and the balance of the load on the different phases.

Because a polyphase meter is subjected to influences tending to increase or modify its inherent error as compared with the error of a single-phase meter, additional clauses are embodied in B.S. 37: 1937, to limit the permissible effect of these disturbances. Correct registration on unbalanced systems and/or loads is dealt with in Clause 50,

which requires that every polyphase meter shall comply with the requirements of the specification, whether the load is balanced or unbalanced. The electrical design of the meter must not be based on a method of measurement which assumes that the load is symmetrical as regards current, voltage or phase angle. The term "polyphase meter" in this clause includes any auxiliary devices such as current and voltage transformers to which it may be connected. These transformers have errors of their own, and when used in conjunction with a meter may tend to increase or modify the meter error. Notwithstanding this fact, the total error of the meter when tested or used with its transformers must not exceed the limits of error laid down in Clause 37, reference to which has already been made on page 107.

It will be appreciated from the foregoing observations that owing to the presence of several disturbing factors in polyphase meters which are absent in the case of single-phase meters, the accuracy of the former cannot be expected to be quite as good as the latter. The majority of single-phase meters manufactured to-day are of the long-range pattern. Some extension of the working range of polyphase meters could be provided, where the whole of the current to be metered is carried by the meter current coils and no current transformers are necessary. The proportion of polyphase meters used with current transformers is very much greater than is the case with single-phase meters and this fact has a considerable bearing on the possibility of obtaining long-range polyphase meters. The working range of a current transformer lies between 120 per cent. and 10 per cent. of the marked current. Below this point the errors of the transformer increase rapidly and impose a limit to the working range of the meter. As a matter of fact, the meter used with transformers is calibrated to cover the range from 125 per cent. to 5 per cent. of the marked current of the transformer, but this range is only achieved with difficulty in some cases. Until current transformers are available having a much greater range of measurement, it is unlikely that long-range polyphase meters will be obtainable to the same extent as is the case with single-phase meters. The same problem arises, of course, where single-phase meters are used with current transformers, but since the majority of circuits carrying heavy currents are metered by polyphase meters, the difficulty is insignificant by comparison.

7.16. Interaction in Polyphase Meters. Polyphase meters are constructed having two driving elements for use on two-phase three-wire, or three-phase three-wire systems, and three driving elements for

use on three-phase four-wire systems: The relative arrangement of the elements has a considerable bearing on the additional errors which are found in polyphase meters, as compared with single-phase In order to avoid interference between one element and another due to magnetic leakage flux, wide separation of the driving elements is desirable. Space considerations however, limit the separation which can be permitted in practice and an unduly large meter would not be viewed favourably by purchasers even though its inherent errors were smaller, apart from which, its cost of production would probably be higher. If the driving elements are placed close together the magnetic fields in the electromagnets must be reduced to a low value to avoid mutual interference and this in turn results in a low driving torque; in some meters a magnetic shield is provided between the driving elements to eliminate or reduce the effect of magnetic leakage.

In addition to magnetic interference the influence of eddy currents induced in the disc by one driving element straying into the area influenced by another driving element must be taken into account. The majority of two-element meters are provided with a separate disc to each driving element and this form of interaction is therefore absent since induced current cannot stray from one disc to another. In the case of three-element meters three separate discs provide for the minimum of interaction. Some manufacturers endeavour to economize in space by arranging two of the driving elements on one disc and the third driving element on a separate disc. This limits any interaction to the two elements which are adjacent. At least two manufacturers supply a meter having three elements driving on to one disc. This arrangement effects a considerable reduction in the overall dimensions of the meter, which is considered to be of overriding importance by some purchasers. To minimize the effect of stray induced current the centre portion of the disc is removed and a centre of glass or other insulating material is substituted. This localizes the area in which the induced current can circulate, and notwithstanding the close proximity of the driving electromagnets to each other it is claimed that the interaction due to stray induced currents and to leakage flux from one electromagnet to another is small.

It is necessary to impose a limit to the effect of interaction in a polyphase meter and this factor is dealt with in B.S. 37: 1937, Clause 52, which states: "For accurate metering it is essential that a polyphase meter shall be connected in accordance with the correct phase-sequence. If this sequence is departed from, however, the errors of the meter

down to 20 per cent. of the marked current only, shall still be within the limits prescribed in Clause 37, with balanced currents in the elements. (See Appendix C (i))". The Appendix states: "This clause has been included to ensure that a meter is reasonably free from interaction under ordinary conditions, but it is necessary to point out that very serious errors may arise with incorrect phase-sequence if the load is out of balance or of low-power-factor".

7.17. Balance of Elements in Polyphase Meters. In order that a meter may register correctly on unbalanced loads, it is essential that the contribution to driving torque by each element shall be the same, for the same load in kW. If one phase only of the supply is loaded at any instant the response of the meter should be the same, irrespective of which phase is carrying the load or of its power-factor. Fulfilment of this requirement is not inherent in a meter but is obtained by means of the various adjustments which are provided. By careful adjustment, the error of a meter can usually be reduced to small proportions under any condition of unbalanced load. The permissible limits of error are dealt with in B.S. 37: 1937, Clause 51, which states with reference to balance of elements: "In a meter having more than one main current coil, the error of the meter down to 20 per cent. of the marked current shall not exceed the limits prescribed in Clause 37 under any condition of unbalanced load (including the case of any one current coil alone being loaded), all the voltage coils being excited at the marked voltage and in the correct phase relationship".

The usual test method of ensuring correct registration on unbalanced loads is to equalize the torques of the driving elements. In a two-element meter, this is accomplished by connecting both the voltage electromagnets in parallel to a single-phase supply at the rated voltage; the current electromagnets are connected in series and one is reversed in direction. Full-load current is passed through both and if each exerts the same torque, no movement of the rotor will take place. If however, one element is stronger than the other the rotor will revolve in the direction exerted by the stronger. The torque may be adjusted by opening or closing the gap between the voltage and current electromagnets on one element until the disc is stationary; usually the current electromagnet is made adjustable for this purpose, but alternatively the voltage electromagnet may be adjustable. As a second alternative the driving element as a whole may be adjustable in a radial direction. In the case of a three-element meter the balancing procedure is followed with any two elements. After obtaining balance on two elements, the

third element is balanced by comparison with one of the others. It is not essential that all the current electromagnets or elements shall be adjustable as one may be a fixture; the other electromagnet or electromagnets may then be balanced against the one which is fixed.

After the adjustment for balance has been made each element is adjusted individually on quadrature to ensure correct registration on inductive loads. The low-load or creep adjustment is then made and this can be effected on any one of the elements; the object of the low-load adjustment is to compensate for frictional retardation in the rotor bearings and the register by the creation of an auxiliary torque just sufficient to overcome friction when there is no load on the meter. Obviously it is immaterial which of the driving elements produces this torque and while most meters are provided with a low-load adjustment on each element, only one is necessary. The main adjustment for full load is made by means of the brake-magnet or magnets. A meter may have one or more magnets and these may be confined to one disc or distributed on all the discs; again, it is immaterial which of the magnets is adjusted if more than one is fitted, and if one driving element causes the rotor to revolve at a higher speed than another on a given load, the error must be rectified by the balance adjustment and not by the brake magnet. Some meter manufacturers supply a polyphase meter having a single brake magnet and notwithstanding the high torque of the meter, the speed of the rotor is no higher than in the case of a single-phase meter with a much lower torque. The brake-magnet must obviously be very powerful to enable this to be achieved, and is usually made from one of the alloy steels such as a 35 per cent. cobalt steel or a nickel-aluminium-cobalt steel.

7.18. Precision Grade Polyphase Meters. Precision grade meters are made in single-phase and polyphase patterns, but little commercial use is made of the former except in test-rooms for sub-standard purposes. Precision Grade polyphase meters are used quite frequently in metering bulk supplies and on generator circuits where large amounts of energy are measured. As a small error on a percentage basis may in such cases represent a considerable sum of money per annum, the cost of expensive metering equipment which will reduce the error to a minimum is well justified. Not infrequently the meters are duplicated in order to reduce still further the possibility of error in measurement. The limits of error for Precision Grade meters, as laid down in B.S. 37: 1937, Clause 37, are the same whether for single-phase or polyphase, and have already

been given on page 108 in dealing with single-phase meters; for convenience they are restated in Table 6 following:

TABLE 6

Limits of Error for Precision Grade Meters.

Current expressed as a percentage of the Marked Current.	125% to 20%	At 10%	At 5%	125% to 20%	At 10%
Power-Factor	1·0	1·0	1·0	0·5 (lag)	0·5 (lag)
Limits of Error	0·5%	1·0%	1·5%	1·0%	2·0%

Bearing in mind that these limits of error include the errors due to unbalanced loads, magnetic interaction between elements, incorrect phase-sequence down to 20 per cent. of marked current, and also errors of current and/or voltage transformers used with the meter, it will be appreciated that transformer errors must be small. In the circumstances the highest class of metering current transformer, i.e. Class AM, must be used. The limits of error for this class are given in Table 7 and for further information on this subject, see Section 12.11, page 422.

It will be observed that the permissible absolute error in ratio on the transformer exceeds the permissible error in the meter at full load; this is not of great importance as the transformer ratio error can be eliminated in the meter calibration. What is important is the *variation* in the error, which cannot be eliminated. Similarly, the phase difference error can be compensated for by the introduction of an equal error in the phase displacement of the voltage flux in the meter. The variation in the error which occurs at various loads cannot be eliminated as the meter can only be corrected for one value, consequently it is necessary to limit the variation. A variation of 15 minutes in the phase difference error will introduce an error in the meter amounting to 0·75 per cent. at 0·5 power-factor. The voltage transformer errors are substantially constant irrespective of the load on the meter, and consequently these can be eliminated or allowed for in calibrating the meter. Voltage transformers of Class B are usually satisfactory for use with Precision Grade polyphase meters.

TABLE 7

Limits of Error for Current Transformers, Class AM.

Absolute Error				Variation in Error	
From 120% to 20% of Rated Current		Below 20% to 10% of Rated Current		From 120% to 10% of Rated Current	
Ratio	Phase Diff.	Ratio	Phase Diff.	Ratio	Phase Diff.
± 1·0%	± 30 min.	± 1·0%	± 30 min.	± 0·5%	± 15 min.

Combined calibration of meter and transformers is desirable if Precision Grade accuracy is necessary, or alternatively calibration of the meter, making due allowance for the transformer errors. The latter method is the more usual and preferable, particularly where the rated current is heavy. It is a simple matter, with suitable equipment, to determine the errors of a current transformer, with an error in measurement not exceeding 0·1 per cent., and if the transformer errors are known the necessary correction can be applied to the meter calibration. If combined calibration of meter and transformers is attempted for current values exceeding say 400 amperes special equipment is essential in order to avoid errors which can be more easily avoided by separate calibration. In any case voltage transformer errors must be dealt with in this manner, as standard testing equipment is not usually available for combined testing of meters and transformers at high voltages. It is perhaps appropriate at this juncture to refer to a precaution necessary when using precision metering equipment. A precision grade meter may be purchased from one manufacturer and Class AM current transformers from another. Each item separately conforms to the accuracy requirements of the relevant specification and it is sometimes assumed that the combination will work together within the limits of error prescribed for the meter. Such however, is not the case and it will be appreciated that the errors in the meter ana the transformers, if of the same sign, may combine to exceed the permissible limits. Only combined calibration, or calibration taking into account the known transformer errors can ensure the desired results.

Precision Grade polyphase meters are usually larger than their Commercial Grade counterparts. This permits wider spacing of the driving elements which is beneficial from the point of view of inter-

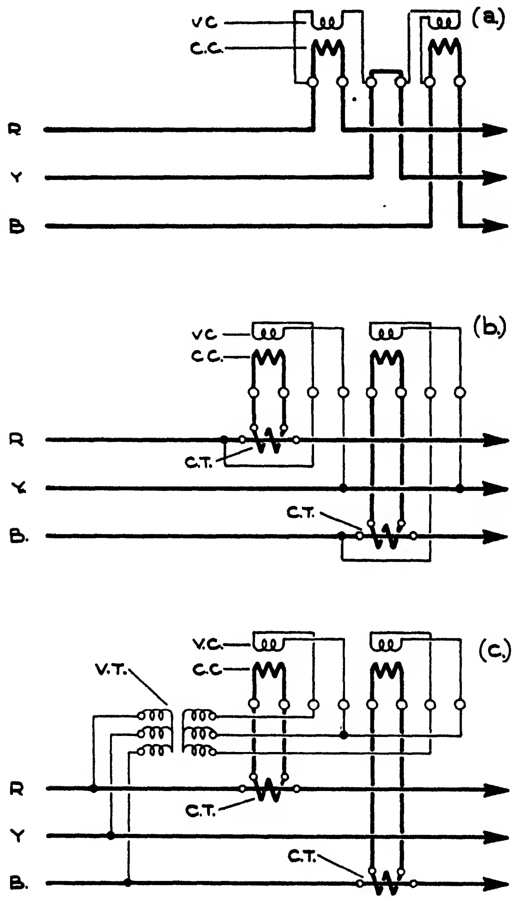


FIG. 107.—Standard connections for three-phase three-wire meters.
(a) Whole current meters.
(b) Meters with current transformers.
(c) Meters with current and voltage transformers.

action. The watt loss and the volt-ampere consumption in the voltage circuits is also higher and the full load speed may be lower. The increased losses in the voltage circuit are well justified in order to obtain

improved accuracy. The torque is higher and one manufacturer provides a magnetic suspension for the rotor, with the object of reducing the pressure between the bottom pivot and jewel.

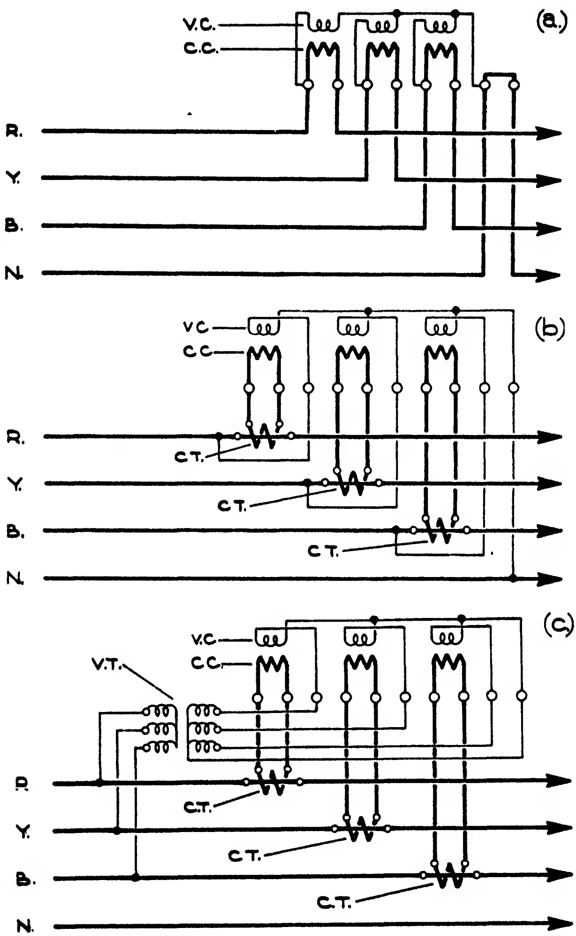


FIG. 108.—Standard connections for three-phase four-wire meters.
(a) Whole current meters.
(b) Meters with current transformers.
(c) Meters with current and voltage transformers.

7.19. Standard Connections for Polyphase Meters. The standard methods of connectihg polyphase meters to the supply lines are shown

in Figs.107 and 108. These call for little comment except to say that meters up to and including rated currents of 50 amperes do not usually require current transformers, if the system voltage does not exceed 600 volts between lines. For voltages in excess of 600 volts, current transformers are required for all current ratings and voltage transformers are also necessary. Voltage transformers are usually three-phase, with the windings connected star-star. In the case of three-phase three-wire meters, two single-phase voltage transformers connected in open delta may be used instead of a three-phase transformer if preferred. The secondary windings of all transformers should be earthed at one terminal.

7.20. Polyphase Meters in Current Production. Polyphase meters are built up from single-phase elements—two in the case of three-phase three-wire meters and three in the case of three-phase four-wire meters. It is customary to utilize, so far as is possible, the same standard parts which are used in the construction of a single-phase meter, and the majority of manufacturers in making a two-element meter arrange the elements vertically one above the other. In such a case the rotor consists of a long spindle having two discs mounted thereon, each disc being driven by the voltage and current electromagnets of one phase of the supply. At least one manufacturer departs from this practice and arranges the two single-phase elements side-by-side, both driving on to one disc.

In the arrangement of the three elements in three-phase four-wire meters there is greater diversity in method. Some manufacturers arrange the three elements vertically one above another, and have a long spindle with three discs, one for each element. Others employ a spindle with two discs, arranging two elements to drive on to the one, and one element to drive on to the other. Two manufacturers use a single disc of large diameter with three driving elements around the circumference and spaced at 90 deg. apart.

Adjustments are provided in all cases for ensuring equality in the driving torque exerted by each element, in order that the meters may be accurate on unbalanced loads. The main speed adjustment consists of one or more brake magnets, and the action of these may be confined to one disc only or they may act on two or three discs. In making an adjustment to the speed of the rotor it is immaterial which brake magnet is adjusted if more than one is provided. Each element has its own inductive-load adjustment; and each must be adjusted independently. It is usual to fit low-load adjusting devices to all elements although this

is not essential since their effects are complementary, and an adjustment made to any one of these will influence all the elements to the same extent.

The majority of manufacturers supply whole-current meters up to

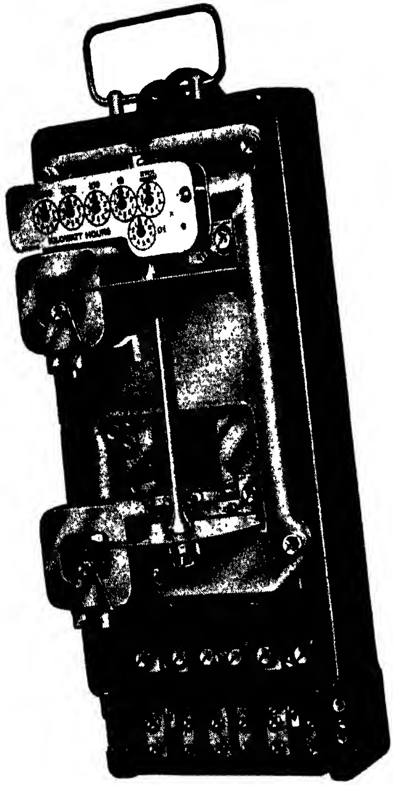


FIG. 109.—Aron three-phase three-wire meter. Type eI33.

50 amperes rating, current transformers being used for currents in excess of this value. A few however, make whole-current meters up to 100 amperes rating. Terminals are usually at the bottom of the meter, but where 100-ampere whole-current meters are supplied, the terminals are arranged on both sides. In the sections which follow, a few examples

of polyphase meters have been selected to illustrate some of the variations in constructional methods which are in current production.

7.21. Aron Polyphase Meter. The three-phase three-wire meter, Type eI33, having two elements mounted vertically, and manufactured by Aron Electricity Meter Ltd., is shown with cover removed in Fig. 109. A cast frame of aluminium-silicon alloy carries at the rear the two single-phase meter elements, and on the front is mounted the rotor, the brake magnets and the register. The top and bottom bearings are retained in position by a bayonet joint which permits quick release, and the bottom pivot of the rotor is of the interchangeable type. By removing the register and the top and bottom bearings the rotor may be withdrawn and replaced without disturbing other parts or affecting the calibration of the meter. The terminal block is secured in the meter case by two screws. In removing these together with the four frame-fixing screws, the meter elements and the terminal block can be withdrawn from the case without disconnecting any of the interior wiring.

Low-load and inductive-load adjustments are provided on each element and are accessible from the front; in addition, each element is fitted with a device for adjusting the balance of torque. This consists of a mild-steel bar arranged across the poles of the voltage electromagnet but separated therefrom by distance pieces. Two steel screws passing through the bar and approaching the centre pole of the electromagnet act as a shunt to the voltage flux; by adjustment of these screws, the torque of each element can be varied to the extent of four per cent. It is desirable that any adjustment be made on the two screws equally in order to avoid disturbing the symmetry of the voltage flux.

7.22. Electrical Apparatus Co., Polyphase Meter. The three-phase four-wire meter, Type EHK3, manufactured by the Electrical Apparatus Co. Ltd., and having three elements arranged vertically, is shown with cover removed in Fig. 110. A cast-metal frame carries all three electromagnet systems on the rear, and at the front is arranged the rotor with its top and bottom bearings, the register and three brake magnets. Each element is provided with independent adjustments for low load, inductive load and balance, and all are accessible from the front. The method of making the adjustments is the same as in the single-phase meter described in Section 3.19. Torque balance between elements is effected by a device operated by two locked screws. Those for the middle element are visible in the illustration to the extreme left and right of the voltage electromagnet, and slightly above the level of the rotor disc.

The terminal block is secured to the metal frame and all connections between the elements and the block are made at the rear. The complete assembly can be removed from the case by withdrawing two frame-

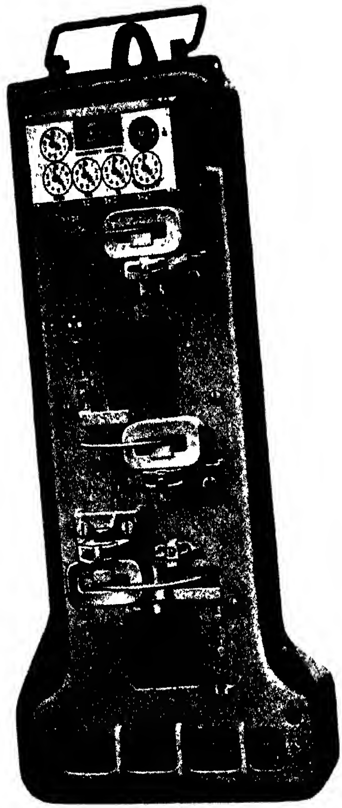


FIG. 110.—Electrical Apparatus Co. three-phase four-wire meter. Type EHK3.

fixing screws and without disturbing any of the internal wiring. This type of meter is self-contained in current ratings up to and including 100 amperes. It is made in the form illustrated in ratings up to 25 amperes, but the 50-ampere and 100-ampere ratings have two terminal blocks arranged one on each side of the meter case.

7.23. Metropolitan-Vickers Polyphase Meter. A three-phase four-wire meter, Type NE4, manufactured by the Metropolitan-Vickers Electrical Co. Ltd., is shown in Fig. 111. The meter illustrated is a semi-switchboard pattern which is identical with the house-service pattern except for the position of the terminals which are at the rear instead of the bottom. In this type of meter the three elements drive a rotor having two discs only. Two elements drive the lower disc and one element drives the upper disc on which the brake magnets also operate. The two elements and supporting frame behind the rotor form a unit substantially

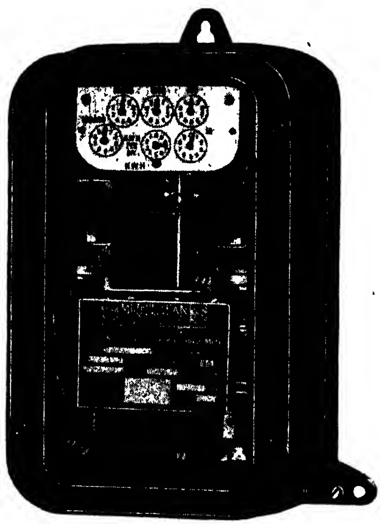


FIG. 111.—Metropolitan-Vickers three-phase four-wire meter. Type NE4.

the same as that in a two-element meter. The third element together with the two brake magnets and register are carried on a separate frame and are supported on the front of the rotor. The advantage of this arrangement is the reduction in the wall space required to accommodate a three-element meter.

The low-load and inductive-load adjustments are similar to those fitted on the Metropolitan-Vickers single-phase meter, Type NE, described in Section 3.20. The full-load adjustment is made by moving one or both of the brake magnets which act on the upper disc. Each is separately adjustable and one has a micrometer movement. Equality

of the driving torques of the three elements is secured by adjusting the position of iron eccentrics located across the leakage gaps of each voltage electromagnet. As the distance of the eccentric from the leakage gap is decreased, the driving torque of the element also decreases; the position of the eccentric can be adjusted by means of wheels operated from the front of the meter. The largest size of whole-current meter of this type is rated at 50 amperes. For currents in excess of this value, a 5-ampere meter is used in conjunction with current transformers.

7.24. Ferranti Polyphase Meter. The three-phase four-wire three-element meter, Type FLx, manufactured by Ferranti Ltd., is of unusual construction. The three driving systems and one braking system

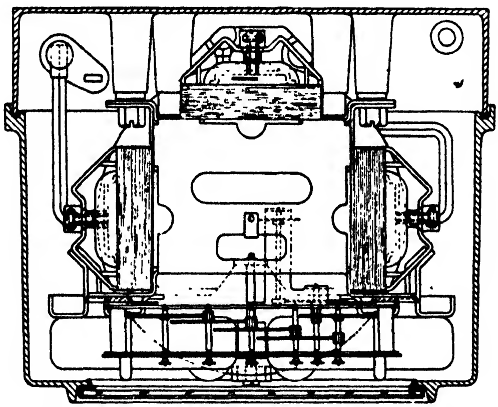


FIG. 112.—Ferranti three-phase four-wire meter. Type FLx.

all act on one disc. This results in a very compact arrangement of the components and the overall dimensions of the meter case are thereby reduced very considerably, compared with what is possible in other constructions. A plan view of the meter elements with the case in section as seen from above the disc, is shown in Fig. 112. It will be observed that the three driving elements are arranged to form three sides of a square with the two brake magnets below the register forming the fourth side. The rotor shaft occupies a central position and is equidistant from each of the driving elements.

The difficulties which may arise in polyphase meters due to interaction between neighbouring elements has been referred to in Section 7.16. That which concerns circulating currents in the disc has been

dealt with in a novel manner and it is claimed by the manufacturers that the performance of this meter is strictly in accordance with the requirements of B.S. 37: 1937.

The rotor disc is comparatively large in diameter, having a centre portion of glass and the outer rim of aluminium. This construction restricts the area within which eddy currents induced by the electromagnets can stray, and minimizes the effects due to interaction. As will be seen in the illustration, the cover of the meter is in close proximity to the brake magnets. To avoid any error due to shunting of the magnet flux, the cover is made of non-magnetic material; this enables tests to be carried out irrespective of whether the cover is on or off. A similar form of construction is adopted in the Ferranti three-phase three-wire two-element meter, Type FLy, the driving element at the rear being omitted in this instance.

7.25. Chamberlain and Hookham Current-Transformer-Operated Polyphase Meter. Polyphase meters for current ratings in excess of 50 amperes usually require current transformers, although a few manufacturers can supply 100-ampere whole-current meters if desired. Generally speaking, the maximum continuous rating of 100-ampere whole-current meters is strictly limited and is much less than the corresponding rating, on a percentage basis, of smaller meters. Thus the time during which an overload can be carried with safety is very short.

When current transformers are necessary, two are used with a three-phase three-wire meter and three with a three-phase four-wire meter. The current transformers are fairly substantial, particularly if of the enclosed pattern and usually occupy more wall space than the meter itself. If of the open type, the transformers must be fitted in some protective enclosure and secondary wiring run from the transformers to the meter. To obviate these disadvantages, the combination of a meter integral with its transformers has been produced by Chamberlain and Hookham Ltd., and designated the "Transformeter", and two views of this instrument are shown in Fig. 113. Apart from the four-wire instrument shown in the illustration, Transformeters are also made for three-wire and single-phase circuits.

The Transformeter shown in the illustration is a three-phase four-wire three-element meter, Type JT4U rated at 200 amperes per phase and the compartment containing the transformers is located at the bottom of the meter case. The ratings in current production are 100, 150, 200 and 300 amperes, and it will be observed that, after installation, the transformers are totally enclosed. The space occupied by the meter,

complete with associated transformers, is very little more than that required for a normal meter of lower current rating, together with its terminal compartment.

The current transformers, which are very small, have nickel-iron ring cores on which the secondary is wound. The primary bar between the terminals is from $\frac{3}{4}$ in. to $1\frac{1}{2}$ in. in length, the higher ratings being

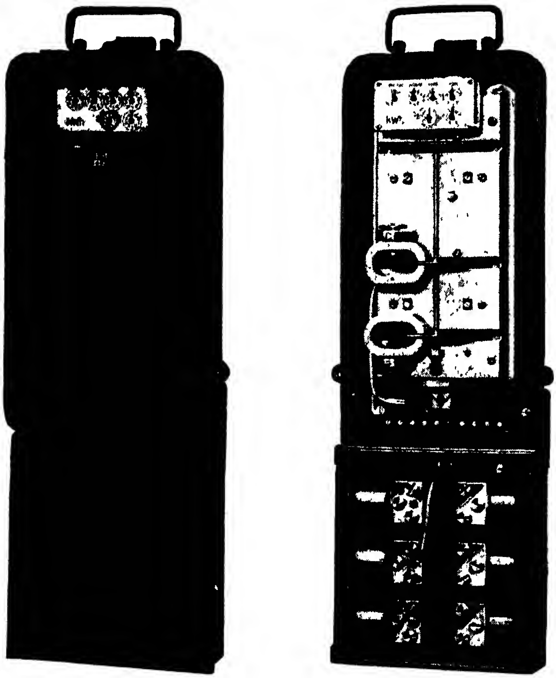


FIG. 113.—Chamberlain & Hookham three-phase four-wire Transformer. Type JT4U.

the shorter, and cable sockets for soldering to the service lines are screwed to substantial end blocks. The volt-ampere rating of each transformer is sufficient for a meter current coil and the very short length of connection between the secondary and the current winding. The voltage leads are connected to each primary and can be disconnected for testing purposes.

Many advantages arise from this arrangement amongst which may be mentioned the following:

1. Reduced space required for the accommodation of the Transformeter and its associated transformers.
2. Reduced time required for testing owing to the absence of externally connected transformers.
3. Reduced time required for installation as there are no separate transformers to fix and no secondary wiring to install. This also reduces considerably the installation costs.
4. No possibility of wrong connections between transformers and meter.

With regard to the last-mentioned advantage, it may be noted that for accurate registration it is essential that on installation each transformer shall be connected to the meter current coil with which it was calibrated. Mistakes in connections between meter and transformers are not infrequent on site, and are not always easy to trace and rectify, particularly if phase and polarity markings are not clear, as they should be, according to B.S. 37: 1937.

CHAPTER VIII

REACTIVE METERS

8.1. Idle Currents in Alternating-Current Circuits. In a direct-current circuit, the power expended is measured in watts and is the product of the voltage at the extremities of the circuit and the current in amperes flowing therein. In an alternating-current circuit the power is also measured in watts, but is not invariably the product of volts and amperes. Instead, the product of volts $\times$ amperes gives the apparent power while the true power is the product of volts $\times$ amperes $\times$ cos ϕ, where the term cos ϕ is the power-factor in the circuit. The alternating-current supply to the ordinary domestic consumer is usually single-phase and as the load consists mainly of lighting and heating appliances, the power-factor approximates to unity, so that the true power is substantially the product of volts $\times$ amperes.

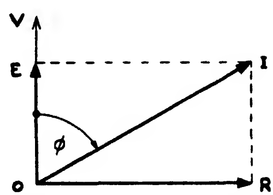


FIG. 114.—Phase relationship between voltage and components of current in single-phase circuit.

OV = Applied Voltage.
OI = Current in circuit.
OE = Energy component.
OR = Reactive component.
ϕ = Phase displacement between voltage and current.

The power consumer on the other hand makes use of apparatus such as motors and transformers which require a magnetizing current lagging 90 deg. behind the applied voltage, in addition to the current which does useful work. The total current in the circuit may be regarded as consisting of two parts, the one a useful or energy component and the other an idle or reactive component. The energy component of the current is proportional to the work done, and is in phase with the voltage applied to the extremities of the circuit. The reactive component is merely a circulating current which does no useful work and

usually consists of magnetizing current which lags 90 deg. behind the applied voltage. In some instances where phase-advancing apparatus such as banks of capacitors or over-excited synchronous motors are employed the reactive component consists of capacitive current which leads 90 deg. in front of the applied voltage.

The relationship between the applied voltage and the components of the current in a single-phase circuit is shown in Fig. 114. The voltage applied to the circuit is represented by the line $O\ V$ and the current in the circuit by the line $O\ I$, displaced in phase from the voltage by an angle ϕ. The current $O\ I$ is the resultant of two components, the one $O\ E$ which is in phase with the applied voltage being the energy component. The reactive component $O\ R$ is displaced 90 deg. out of phase with the applied voltage and may be lagging or leading according to whether the load is inductive or capacitive.

When energy is supplied to a consumer of electricity, and is charged for on the basis of the kilowatt-hours expended, the meter will register the product of the voltage and the "in phase" component of the current, that is to say, the energy component $O\ E$. If the power-factor of the circuit is unity, as is usually the case with domestic consumers, the total current $O\ I$ will coincide in phase with $O\ E$ and there will be no reactive component $O\ R$. On the other hand, a power consumer having a load made up largely of induction motors, will probably take current from the supply, consisting in part of a reactive component, and consequently the total current $O\ I$ will not be in phase with the voltage $O\ V$. The kilowatt-hour meter however, will not register the reactive component but only the energy component, and in terms of current, the rotor speed will be proportional to $O\ I \cos \phi$ which is equal to $O\ E$.

It will be appreciated that in such a case the consumer takes current from the supply for which no direct charge is made. The presence of reactive current in the generating and distributing system of a supply undertaking is disadvantageous from several points of view. The output of generators and transformers and the current-carrying capacity of a distributing system is reduced if part of the output consists of reactive current, besides which, there is an actual loss of power resulting from the additional current flowing in the system, above that which is doing useful work.

The actual cost of generating reactive current is small, but since the output of plant and the current-carrying capacity of the distribution system, measured in terms of useful current, is reduced when reactive current is present, the capital costs incurred in supplying current to a

consumer with a power-factor less than unity are increased. It follows therefore that such a consumer should in equity pay the additional cost of supplying reactive current. In the case of small consumers the extra cost of the metering equipment necessary for measuring the reactive current is not justified, but for large power consumers this additional equipment is frequently installed and provides the means whereby the consumer with a low power-factor can be encouraged to improve this undesirable condition or alternatively can be penalized if he allows the condition to persist.

A kilowatt-hour meter is always used for measuring the energy component $O\ E$ of the current and because it measures the quantity, volts $\times$ amperes $\times$ hours $\times$ cos ϕ, it is sometimes referred to as a cosine meter, when meters for measuring other quantities also are being considered. The meter which is used for measuring the reactive component $O\ R$ of the current, is variously described as a reactive meter, a wattless-component meter, or a sine meter, the latter expression being derived from the fact that it measures volts $\times$ amperes $\times$ hours $\times$ sin ϕ, where, as before, ϕ is the angle of phase displacement, lagging or leading, between the applied voltage and the current in the circuit. The term "reactive meter" is generally to be preferred and the symbolic expression VArh may be used to represent the quantity measured.

A meter which measures the current $O\ I$ in the circuit and is not influenced by the power-factor may be described as an ampere-hour meter, and if it is associated with a voltage measuring element, it may be more correctly described as a voltampere-hour meter or kilo-volt-ampere-hour meter. The abbreviation kVAh meter, is commonly employed but as in this case such a meter is usually associated with a demand indicator which gives an indication of the average value of the product of volts $\times$ amperes over an interval of time, the term "kVA meter" is more appropriate.

8.2. Reactive Meters. In construction, a reactive meter is usually identical in appearance with an ordinary induction type kilowatt-hour meter but differs in the method of connection of the windings to the various phases of the supply. Its function is to measure the reactive component of the current which is 90 deg. out of phase with the applied voltage in an alternating current circuit. The current may be lagging or leading according to whether the circuit comprises power using devices which require a magnetizing current, or power-factor correcting devices such as capacitors or over-excited synchronous motors. A reactive meter arranged to run in the forward direction when the current is

lagging will, for a particular value of the current, run at its maximum speed when the current lags exactly 90 deg. that is when the power-factor is zero. At any other power-factor the speed of the rotor will be reduced and at unity power-factor, corresponding to zero phase displacement between current and voltage, the speed of the rotor will also be zero. If now, the current should lead the voltage, the direction of rotation will be reversed and the speed of the rotor will increase as the angle of lead increases until, with a 90 deg. lead, the speed of the rotor will again reach a maximum but in the reverse direction for a particular value of the current. The speed of the rotor will at all times be proportional to the product of volts $\times$ amperes $\times$ sin ϕ, where ϕ is the angle of phase displacement, lagging or leading, between current and voltage in the circuit.

The performance of a reactive meter differs from that of an energy meter in that the latter registers in the forward direction irrespective of whether the current is lagging or leading, and the speed of the rotor is at a maximum for a particular value of the current when the power-factor is the highest, whereas a reactive meter registers in the forward direction for a lagging current and backward for a leading current, the rotor speed being highest when the power-factor is the lowest. A further point is than an energy meter is capable of its best performance when the power-factor is unity, and a reactive meter when the power-factor is zero. The inherent accuracy of a reactive meter is not as good as that of an energy meter owing to limitations in design to which reference will be made later in this chapter.

Since the direction of rotation of the rotor in a reactive meter depends upon whether the power-factor is lagging or leading, it follows that it will also be influenced by phase sequence. In all the diagrams which follow it will be assumed that the standard phase sequence is observed, that is, the order of the phases is R Y B. In the vector diagrams phase rotation is anti-clockwise, and is indicated on the diagram by an arrow. If a reactive meter is connected up with phase sequence reversed the direction of rotation of the rotor will also be reversed.

8.3. Single-Phase Reactive Meters. A reactive meter for operation in a single-phase circuit where a single-phase supply only is available would consist of a voltage electromagnet and a current electromagnet arranged exactly as in a single-phase energy meter. The phase relationship between the voltage flux and the current flux would however be different. In Chapter IV dealing with the theory of the induction meter, it was explained that in a watt-hour meter, the voltage flux lags 90 deg. behind

the voltage applied to the terminals of the voltage electromagnet, whereas the current flux is in phase with the current in the main circuit; in these circumstances the voltage flux lags 90 deg. behind the current flux when the power-factor of the load is unity, and the fluxes are in phase when the power-factor of the load is zero, lagging. In a single-phase reactive meter the voltage and current fluxes are in phase (or phase opposition) when the power-factor is unity. The current flux lags 90 deg. behind the voltage flux when the power-factor is zero, lagging, and leads by 90 deg. when the power-factor is zero, leading.

It is not a simple matter to obtain coincidence in the phase of the voltage and current fluxes. The current electromagnet presents no difficulty since this forms a small part of the main circuit in which the load is connected. The impedance of the current coil is negligible by comparison with the impedance of the main circuit and consequently the phase of the current flux is determined by the power-factor of the load. The voltage electromagnet on the other hand is normally highly inductive and the current in the voltage coil lags nearly 90 deg. in a watt-hour meter. In order to reduce the lag of current in the voltage coil, a high resistance may be connected in series. However high the resistance may be, it cannot reduce to zero the reactance of the voltage coil and consequently the current must still lag substantially, apart from which, the watt-loss in the voltage circuit will be very high compared with the watts usefully employed in the voltage electromagnet.

Some manufacturers have employed a capacitor in series with the voltage coil in order to introduce a leading component into the circuit. Others have adopted a parallel arrangement of coils on the voltage electromagnet, one of the coils being connected in opposition to the other. An adjustable resistor is inserted in series with one of the coils; this enables an approach to phase-opposition between applied voltage and voltage flux to be achieved. The phase of the current flux can also be altered by connecting a non-inductive resistance in parallel with the current coil or by fitting a heavy short-circuited loop on the current electromagnet. By a combination of two or more of these expedients, phase similarity or phase opposition between voltage and current fluxes can be obtained, but all such arrangements suffer from the disadvantage that they are more or less seriously affected by variations in frequency or wave form. A reactive meter designed on these lines cannot compare in accuracy with the results obtainable in the corresponding energy meter. Fortunately the necessity for using reactive

meters on single-phase circuits seldom occurs and in the case of polyphase circuits, other means are available for obtaining the desired results.

8.4. Polyphase Reactive Meters. Reactive meters for use in polyphase circuits are usually indistinguishable from energy meters, so far as appearances go, and differ only in the arrangement of the connections and the provision of a ratchet and pawl device to prevent backward rotation. As already explained, a reactive meter which is intended to measure the reactive component of a lagging current will run in the forward direction when the current is lagging and in the backward direction when the current is leading. If, in a particular case, lagging and leading power-factors are experienced and no provision is made for discrimination, the backward registration when the power-factor is leading will tend to cancel the forward registration when the power-factor is lagging. It is usual in such a case to provide two meters connected in series, one of which has the connections to its current coils reversed, and both having ratchet and pawl devices to prevent backward running. One meter will then run forward when the current is lagging and the other will run forward when the current is leading. As neither meter will register in the reverse direction, a registration may thus be obtained of the consumption on lagging and leading power-factors respectively.

The energy component in an alternating-current circuit is proportional to $E \times I \times \cos \phi$, and the reactive component to $E \times I \times \sin \phi$. But $E \times I \times \sin \phi = E \times I \times \cos (90^\circ - \phi)$. A little consideration will show that if we take an ordinary single-phase energy meter which measures $E \times I \times \cos \phi$ and connect its voltage coil to a circuit the voltage of which lags 90 deg. behind that to which it is normally connected, it will register at a rate proportional to $E \times I \times \cos (90^\circ - \phi)$ or to $E \times I \times \sin \phi$. This in fact is the underlying principle usually adoped in metering the reactive component in polyphase circuits and is a much simpler solution of the problem than those referred to in an earlier paragraph. A polyphase reactive meter consists of two or more single-phase elements and usually in each the voltage coil is connected to a phase not directly associated with its current coil. In the case of three-phase circuits, this may involve the selection of a voltage which differs in magnitude from that which is required, but means are readily available for making the necessary correction and these will be described in the succeeding paragraphs.

8.5. Two-phase Reactive Meters. The measurement of the reactive

component in a two-phase circuit is accomplished in a very simple manner. Two single-phase meters may be used, each of which measures the quantity in one phase, or preferably a two-element meter which will give the total reactive kVAh on one register. The diagram in Fig. 115 shows the arrangement of the connections for a two-phase three-wire supply. The current coils of the two meter elements M_R M_B are connected in the red and blue phases respectively. The voltage coil associated with the red current coil is connected between the neutral and the blue line; the voltage coil associated with the blue current coil is connected between the red line and neutral. Single-phase loads may be connected as at L_1 and L_2. In addition, a load may be connected across the outers of the system as at L_3 and in this case the voltage will be $\sqrt{2}$ times the voltage applied to the loads L_1 and L_2.

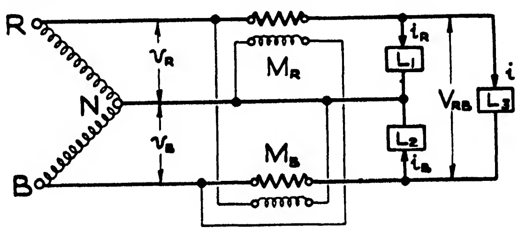


FIG. 115.—Connections for two-phase three-wire reactive meter.

The vector diagram in Fig. 116 shows the phase relationship between the currents and voltages in the meter elements with a lagging power-factor of 0·7 approximately when the loads L_1 L_2 only, in Fig. 115 are being supplied. The current i_R in the red current coil of M_R, due to the load L_1 is lagging behind the voltage v_R in the red phase by an angle ϕ_R. The current i_B in the blue current coil of M_B due to the load L_2 is lagging behind the voltage v_B in the blue phase by an angle ϕ_B. The voltages v_R and v_B are displaced 90 deg. apart with v_R lagging. By associating in one meter element a current derived from one phase with the voltage derived from another which lags 90 deg. behind the first, the reactive component is measured by means of an ordinary energy meter element without any constructional modification being necessary.

The voltages v_R and v_B are assumed to be equal and accordingly the current i_B in the blue phase is associated with the voltage v_R across the red phase. Similarly, the current i_R in the red phase is associated with the voltage $-v_B$ which is the voltage v_B across the blue phase,

reversed. Consideration of the vector diagram will show that when the loads L_1 and L_2 are non-inductive and the power-factor is unity, the currents i_B and i_R will be leading by 90 deg. on the voltages v_R and $-v_B$ with which they are respectively associated, and consequently there will be zero registration on the two meter elements M_R and M_B. As the power-factor in the circuit changes and the current lags, the phase displacement between current and voltage in the meter windings becomes progressively less, until finally with zero power-factor the current is lagging 90 deg. If the current is maintained at a steady value while the power-factor is reduced the speed of the rotor will increase and will reach a maximum value when the power-factor is zero.

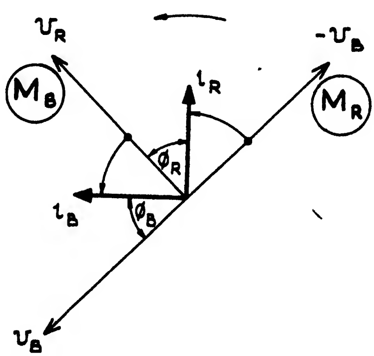


FIG. 116.—Vector diagram for two-phase three-wire reactive meter.

The reactive component of the power supplied to the load is equal to $E \times I \times \sin\phi$ where ϕ is the phase displacement between the voltage E and the current I in the load circuit. The reactive component measured by a wattmeter connected as at M_B in Fig. 115 is equal to $v_R \times i_B \times \cos(90° - \phi_B)$. But $\cos(90° - \phi_B) = \sin\phi_B$ and since the voltages v_B and v_R are assumed to be equal we may substitute as the reactive component measured at M_B, the expression $v_B \times i_B \times \sin\phi_B$, which corresponds to $E \times I \times \sin\phi$. A watt-hour meter connected as at M_B will register during a time interval of t hours the quantity $E \times I \times t \times \sin\phi$, which is the reactive volt-ampere-hours expended in the load L_2. If the loads L_1 L_2 are balanced, the total quantity registered will be $2\,(E \times I \times t \times \sin\phi)$.

We may now consider the effect of a single-phase load connected across the outers RB as at L_3 in Fig. 115. If the load is non-inductive,

there will be no reactive component in the power circuit and consequently no registration should occur. If a two-element meter is used, there will be no registration, but if two separate meters are used as at M_R M_B, the result may be somewhat unexpected, as one meter will register in the forward direction and the other in the reverse direction, the rate of each being the same. As the load becomes inductive, the rate of the forward meter will increase and the reversed meter will slow down until a power-factor of 0·707, corresponding to 45 deg. lag is reached when the reversed meter will cease to register. The two-element meter under

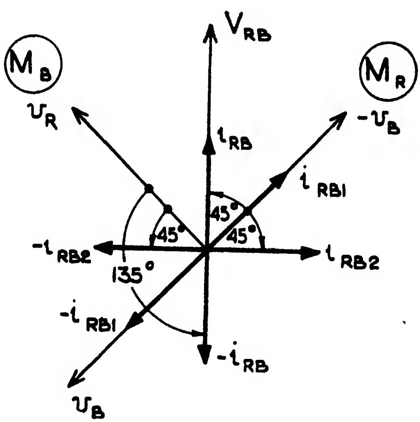


FIG. 117.—Vector diagram for two-phase three-wire reactive meter, with load between red and blue lines.

this condition will register in the forward direction. Further reduction in the power-factor will result in both the separate meters registering in the forward direction until, with zero power-factor, each will register at the same rate. This behaviour is quite correct and it will be found that at any power-factor the sum of the registrations on the two separate meters will be the same as the registration on the two-element meter.

It will be obvious that where separate meters are used, ratchet and pawl devices should not be employed as these will prevent reverse rotation and consequently will result in the total amount registered being incorrect. Preferably, a two-element meter should be used as this will avoid the possibility of such an error arising.

The reason for the two separate meters behaving differently will

be seen by reference to the vector diagram in Fig. 117. When the power-factor is unity the current taken by the load L_3 which is connected across the red and blue lines in Fig. 115 is represented by the vector i_{RB} in phase with the voltage V_{RB}. In the meter element M_R this current is associated with the reversed voltage $-v_B$ which it leads by 45 deg. In the meter element M_B, the current is reversed in direction through the current coil and is represented by the reversed current vector $-i_{RB}$ with which is associated the voltage vector v_R. The current vector in this case is leading by 135 deg. in advance of the voltage vector.

The meter element M_R tends to register at a rate proportional to

$$E \times I \times \cos 45^\circ$$

and the meter element M_B at a rate proportional to

$$E \times I \times \cos 135^\circ$$

where E is the voltage between line and neutral (balanced voltages assumed).

$$\text{But } \cos 135^\circ = -\cos (180^\circ - 135^\circ) = -\cos 45^\circ$$

The registration on meter element M_B is therefore proportional to

$$E \times I \times \cos 135^\circ = E \times I \times -\cos 45^\circ$$

This is a negative quantity indicating that the registration is in the reverse direction, and as the two registrations are numerically equal and opposite, the net registration is zero. This is as it should be, since with a non-inductive load, there is no reactive component in the current.

Consider now, the case where the current in the load L_3 is lagging 45 deg., corresponding to a power-factor of 0·707. This condition is shown in Fig. 117 by the current-vectors i_{RB1} and $-i_{RB1}$. The current represented by i_{RB1} is now in phase with the voltage represented by $-v_B$ in the meter element M_R. The current represented by $-i_{RB1}$ is leading by 90 deg. in advance of the voltage represented by v_R in the meter element M_B. The total amount registered by the two elements M_R and M_B is proportional to

$$(E \times I \times \cos 0^\circ) + (E \times I \times \cos 90^\circ)$$

As $\cos 0^\circ = 1$ and $\cos 90^\circ = 0$ this expression becomes

$$(E \times I \times 1) + (E \times I \times 0) = E \times I$$

where E is the voltage between line and neutral on each phase (balanced

voltages assumed). The voltage across the load is the voltage between the outers *RB* of the two-phase supply system (see Fig. 115) and as the current is lagging 45 deg. behind this voltage the reactive power expended in the load is equal to:

$$\sqrt{2} \times E \times I \times \sin 45° = \sqrt{2} \times E \times I \times 0{\cdot}707 = E \times I$$

which is the quantity being measured by the one meter element M_R.

Finally, the hypothetical case of the current lagging 90 deg. in the load L_3, corresponding to zero power-factor, may be considered. In the meter element M_R the current represented by i_{RB2} is lagging 45 deg. behind the voltage represented by $-v_B$. In the meter element M_B, the current represented by $-i_{RB2}$ is leading 45° in advance of the voltage represented by v_R. The total amount registered by the two meter elements M_R and M_B is proportional to

$$(E \times I \times \cos 45°) + (E \times I \times \cos 45°) = 2\,(E \times I \times 0{\cdot}707) = \sqrt{2} \times E \times I.$$

and this quantity is equal to the reactive power in the circuit which is

$$\sqrt{2} \times E \times I \times \sin 90° = \sqrt{2} \times E \times I$$

8.6. Reactive Meters for Three-Phase Three-Wire Circuits. Much ingenuity has been expended in devising arrangements for the measurement of the reactive component in three-phase circuits. Most of these depend for their accuracy on the assumption that either the line currents, or voltages, or both, are balanced. The assumption that line currents will be balanced is seldom justified and the amount of unbalance experienced in practice is sufficient to render this method unacceptable in the majority of cases owing to the errors which result. Voltage unbalance on the other hand is comparatively small under normal conditions and the errors resulting from this assumption are generally accepted as being of negligible proportions.

Without seeking to justify errors in reactive meters, it may be pointed out that the necessity for a close degree of accuracy in measurement is not so great as in the case of energy meters. It is seldom that a direct charge is made for the reactive kVA hours registered, and even should this be the case, the monetary value of a number of reactive kVA hours is very substantially less than the value of a corresponding number of kW hours. When a reactive meter is employed its function usually is to enable the power-factor at the time of maximum demand to be determined, or to obtain the average value of the power-factor over a period of time; alternatively it may be used in conjunction with an energy meter to determine the maximum demand in kVA. In either

case, an error of "x" per cent. in the reactive meter will introduce an error of less than "x" per cent. in the value of the quantity to be determined.

Where a test is being undertaken and it is desired to ascertain the approximate power-factor from the meter readings, many methods are available for its determination which assume that the currents are balanced. Insofar as the factors which introduce error are known, the use of these methods may be justified, but for metering purposes over long periods, during which conditions affecting accuracy may vary, it is preferable to confine the method to one in which the only assumption made is that voltages will be balanced.

8.7. Three-Phase Three-Wire Reactive Meter with Three Elements. A reactive meter having three measuring elements and suitable for use on a three-phase three-wire supply is connected as shown in Fig. 118. It is provided with three current coils connected one in each of the three lines, and three voltage coils connected in delta. The phase relationship between the applied voltages and the currents is shown in the vector diagram in Fig. 119. The current vectors I_R I_Y I_B indicate the condition when the power-factor is unity, and I_{R1} I_{Y1} I_{B1} when the power-factor is zero. At unity power-factor, there is in each element of the meter, a phase difference of 90° between the applied voltage and the current, which latter is in advance of the voltage. With quadrature between the two there is no registration. At zero power-factor the applied voltage and the current in each element are in phase and the rate of registration is at a maximum for any particular value of the current.

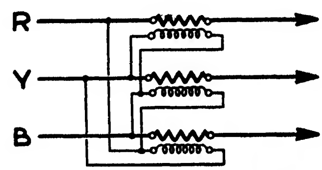


FIG. 118.—Three-phase three-wire reactive meter with three elements.

The reactive power in each phase is equal to $e \times I \times \sin \phi$. Assuming the power-factor to be the same in each phase, and the loads to be balanced, we have:

$$Q = 3 \times e \times I \times \sin \phi$$
$$= \sqrt{3} \times E \times I \times \sin \phi$$

where Q = total reactive power
e = voltage between line and neutral
I = current in each line
E = voltage between lines
ϕ = angle of displacement between voltage and current

T

A voltage, equal in magnitude to the line to neutral voltage but displaced 90° lagging therefrom, should be applied to each element of the meter. The only voltage available is the voltage between lines and while this is correct as regards phase displacement it is incorrect as regards magnitude in the ratio of $\sqrt{3}: 1$. As a result, the meter registers at a rate proportional to $3 \times E \times I \times \sin\phi$ and it is necessary to divide the registration by $\sqrt{3}$ to obtain the correct amount. In order to avoid calculation, the gearing of the register is suitably arranged to register

$$\begin{aligned} Q &= 3 \times E \times I \times \sin\phi/\sqrt{3} \\ &= 3 \times e \times I \times \sin\phi \end{aligned}$$

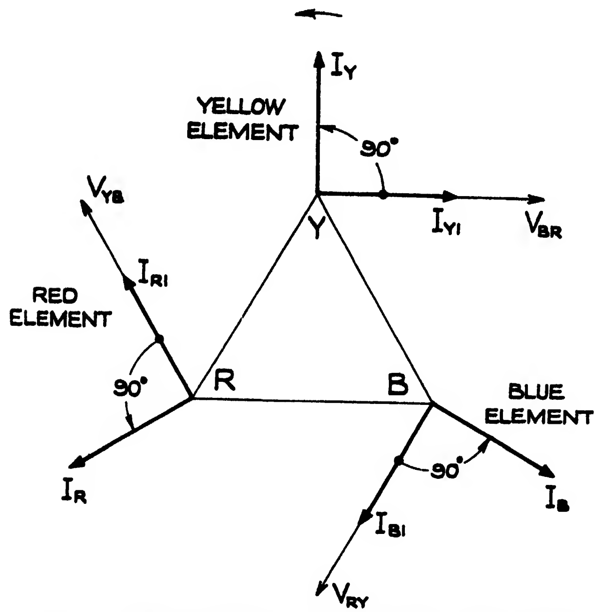


FIG. 119.—Vector diagram for three-element reactive meter.

This type of meter provides very good accuracy on balanced or unbalanced loads provided that the voltages are balanced. Even if the voltages are unbalanced to a small extent, the errors may still be regarded as relatively unimportant on this account. The meter is not used extensively however, because, having three elements, three current transformers are necessary on high voltage or heavy current circuits, whereas two-element meters requiring two transformers only are available with comparable accuracy under similar conditions.

8.8. Three-Phase Three-Wire Reactive Meter with Artificial Neutral. This type of meter has two elements and is supplied with an externally-connected reactance coil. The connections are arranged in accordance with the diagram in Fig. 120. There are two current coils in the red and blue lines respectively and two voltage coils which, when associated with an external reactance, enable an artificial neutral point to be established. The external reactance usually consists of an electromagnet identical to the voltage electromagnets in the meter, and housed in a suitable protective casing. All three electromagnets are selected to have matched impedances and the reactance coil external to the meter is usually fitted with an adjustment in the form of a magnetic shunt. By means of this adjustment, a slight variation in the impedance can be made, so that an artificial neutral point can be created at the junction of the three coils corresponding to the neutral of the supply system. This avoids the necessity for obtaining access to the system neutral, as the latter is frequently not available where a three-phase three-wire supply is provided. The use of the artificial neutral is also preferable to the system neutral, since the latter is not necessarily the true neutral point, but varies with the loading on the supply system and results in the application of unbalanced voltages to the meter voltage coils; the artificial neutral is not influenced to the same extent by load conditions and consequently may be relied upon to assure greater accuracy in registration.

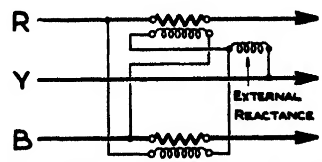


FIG. 120.—Three-phase three-wire reactive meter with artificial neutral.

The vector diagram in Fig. 121 shows the phase relationship between the voltage and current in the two meter elements. In the red element, the voltage applied to the voltage electromagnet is taken between the neutral and the blue line, and is represented by the vector v_{NB}. When the load is non-inductive, the current I_R in the red current coil is leading 60 deg. in front of the voltage v_{NB}. In the blue element, the voltage applied to the voltage electromagnet is taken between the red line and neutral and is represented by the vector v_{RN}. When the load is non-inductive, the current I_B in the blue current coil is leading 120 deg. in front of the voltage v_{RN}.

At unity power-factor there is no reactive power in the circuit. The rate of registration of the meter is proportional to the resultant of the torques developed by the two separate elements.

Assuming balanced voltages and currents, we have :

$$v_{NB} = v_{RN} = e$$
$$\text{and } I_R = I_B = I$$

Accordingly, the rates at which the elements tend to register will be proportional to :

Red element: $e \times I \times \cos 60^\circ$
Blue element: $e \times I \times \cos 120^\circ$
But $\cos 120^\circ = -\cos (180^\circ - 120^\circ) = -\cos 60^\circ$

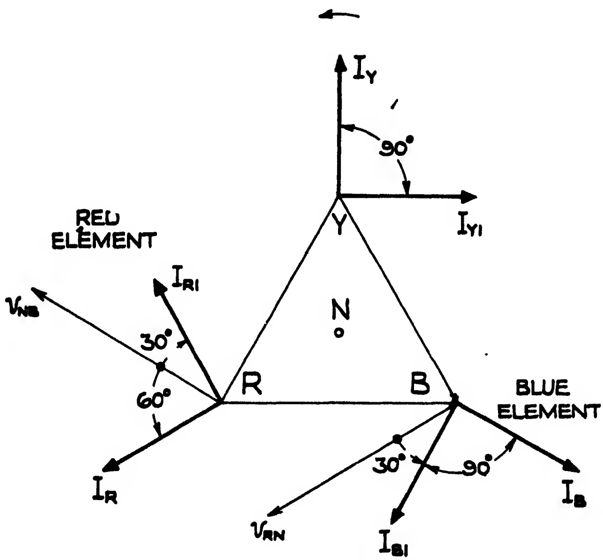


FIG. 121.—Vector diagram for reactive meter with artificial neutral.

The rate of registration on the meter is therefore proportional to:

$$(e \times I \times \cos 60^\circ) + (e \times I \times -\cos 60^\circ)$$

These two expressions are numerically equal, but the second is a minus quantity indicating that the blue element tends to rotate backwards at the same rate that the red element tends to rotate forwards, the net result being that the rotor of the meter remains stationary.

At zero power-factor the current in each line lags 90° and the current vectors are displaced to the positions shown at I_{R1} and I_{B1}. The current I_{R1} in the red current coil now lags 30 deg. behind the voltage v_{NB} with

which it is associated, and the current I_{B1} in the blue current coil leads by 30 deg. on its associated voltage v_{RN}. The rates at which the elements now tend to register are proportional to:

Red element: $e \times I \times \cos 30°$
Blue element: $e \times I \times \cos 30°$

The rate of registration on the meter will be proportional to the sum of these expressions, that is:

$$\begin{aligned} & 2\,(e \times I \times \cos 30°) \\ = {} & 2\,(e \times I \times 0{\cdot}866) \\ = {} & \sqrt{3} \times e \times I \end{aligned}$$

The correct rate of registration at any power-factor is proportional to:

$$\sqrt{3} \times \mathrm{E} \times \mathrm{I} \times \sin \phi$$

where ϕ is the angle of displacement between current and voltage in the circuit. At zero power-factor the current lags 90 deg. and sin 90 deg. $= 1$. The expression therefore becomes $\sqrt{3} \times E \times I$.

The difference between the rate $\sqrt{3} \times e \times I$ at which registration takes place, and $\sqrt{3} \times E \times I$, the correct rate, is due to the fact that the voltage elements of the meter are energized by line to neutral voltage instead of voltage between lines. In a time interval t, the amount registered in reactive kVA hours will be $\sqrt{3} \times e \times I \times t \times \sin \phi$ which when multiplied by $\sqrt{3}$ gives the correct quantity. It is more usual however, to arrange the train of wheels to run at $\sqrt{3}$ times the normal rate in order to avoid the necessity for this multiplication.

Comparing the behaviour of this reactive meter with a normal two-element three-phase three-wire energy meter, it may be noted that the reactive meter at zero power-factor (lagging) is in the same condition as the energy meter at unity power-factor. The reactive meter at unity power-factor is in the same condition as the energy meter at zero power-factor (leading).

8.9. Three-Phase Three-Wire Reactive Meter with Auto Transformers. This form of reactive meter has two measuring elements and the phase relationship between the voltage and current applied to the driving electromagnets is identical to that in the reactive meter with artificial neutral, described in the previous paragraphs. It differs in that the voltage applied to the voltage electromagnets corresponds in magnitude to the voltage between lines and consequently no multiplying factor

need be employed. The method involves the use of two auto-transformers and some additional complication in the connections of the associated voltage circuits. The ratio and phase displacement errors of these auto-transformers must be allowed for in calibrating the meter and combined calibration is essential if the minimum meter error is desired. In the case of high voltage metering the additional burden on the voltage transformer due to the use of the auto-transformers may be a disadvantage, but this will not arise in the case of low voltage metering.

The connections are shown in Fig. 122 from which it will be noted

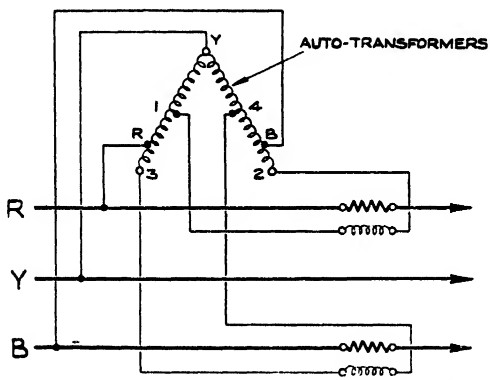


FIG. 122.—Three-phase three-wire reactive meter with auto-transformers.

that the auto-transformers are connected to the supply mains in open delta. Each transformer has two tapping points in addition to the two terminals at the extremities of the winding. Considering the transformer connected between the red and yellow lines, a potential difference of 115·5 volts will be obtained across the extremities 3 — Y and 57·7 volts across the terminals 1 — Y when 100 volts are applied to the terminals R — Y. Similar voltages will be obtained from the other transformer in similar circumstances and the ratio of the voltages will remain the same, whatever the magnitude of the supply voltage may be.

A voltage triangle for the transformers when connected in open delta to a three-phase supply, is shown in Fig. 123. The difference in potential between the mid-point tapping of either transformer and the free extremity of the other will be the same as the applied voltage;

further, the phase displacement will be 90 deg. between terminals 1 — 2 and R — Y as also between terminals 3 — 4 and Y — B. The vector diagram in Fig. 121 for a meter with external reactance will apply equally in this case, the only difference being that the voltage vectors v_{NB} and v_{RN} will become v_{12} and v_{34} respectively. Since the output voltages applied to the meter voltage coils are equal to the line voltages applied to the auto-transformers, the meter will register reactive kVA-hours at a rate proportional to $\sqrt{3} \times E \times I \times t \times \sin \phi$ without the use of a multiplying factor.

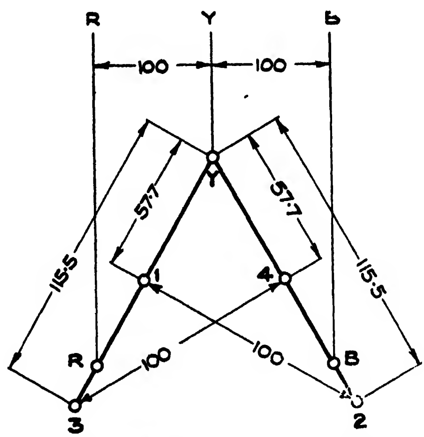


FIG. 123.—Voltage triangle for auto-transformers connected in open delta.

8.10. Three-Phase Three-Wire Reactive Meter with Internal Compensation. The polyphase reactive meters already referred to have been constructed with voltage and current electromagnets identical with those used in meters for the measurement of the energy component. The one now about to be described differs in that the phase displacement between voltage flux and current flux is reduced. In an energy meter the voltage flux lags 90 deg. behind the voltage applied to the terminals of the voltage electromagnet and the current flux is in phase with the current in the main circuit. Thus there is a phase difference of 90 deg. between the voltage and current fluxes when both electromagnets are energized from the same phase and the power-factor of the circuit is unity.

In the meter now under consideration the phase displacement between voltage flux and current flux is 60 deg.; this is accomplished

partly by the use of a short-circuited winding on the current electromagnet and partly by the insertion of resistance in series with the winding on the voltage electromagnet. The effect of the short-circuited winding is to cause the current flux to lag and thus to approach the voltage flux which is already lagging. The effect of the resistance in series with the voltage electromagnet is to reduce the lag of the voltage flux and thus to approach the current flux; the combined effect of these two changes in phase displacement is to reduce the normal phase difference from 90 deg. to 60 deg.

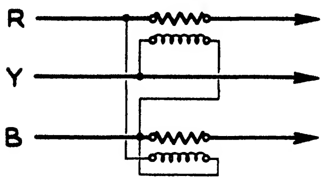


FIG. 124.—Three-phase three-wire reactive meter with internal phase compensation.

The method of connecting the meter is shown in Fig. 124, from which it will be noted that the current coil in the red line is associated

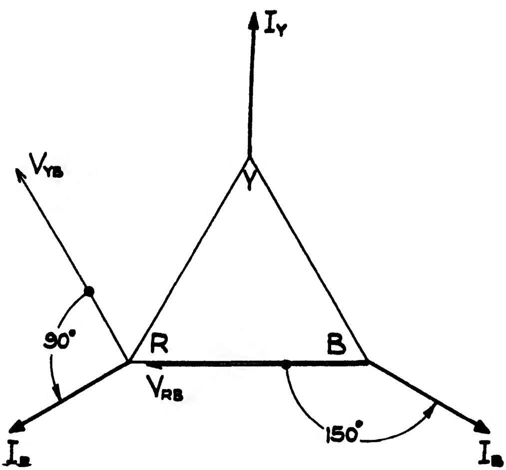


FIG. 125.—Vector diagram for internally compensated reactive meter.

with a voltage coil connected between the yellow and blue lines; the current coil in the blue line is associated with a voltage coil connected between the red and blue lines. The phase relationship between these currents and voltages is shown in the vector diagram Fig. 125, which

refers to the condition when the power-factor is unity. Bearing in mind that the voltage flux in this type of meter, lags 60 deg. behind the applied voltage, it will be seen from the vector diagram that the voltage flux resulting from the applied voltage V_{YB} will be in phase with the voltage across RY.

On referring to the vector diagram in Fig. 121 which concerns a reactive meter in which the voltage flux lags 90 deg. behind the applied voltage it will be observed that in this case also the voltage flux resulting from the applied voltage v_{NB} is in phase with the voltage across RY. Similar reasoning will show that the voltage flux in the blue element is in both cases in phase with the voltage across YB. Thus, the phase displacement between the voltage and current fluxes produced by the driving electromagnets in a reactive meter is the same, irrespective of the means employed to obtain it.

The advantage claimed for this type of reactive meter is that no external auxiliary device such as an auto-transformer or a reactance coil is necessary and to this extent the connections of the meter to the external circuit are simplified. The magnitude and phase of the voltages already available in the supply system are suitable for direct application to the meter voltage coils and consequently no multiplying factor has to be employed in order to arrive at the correct registration. On the other hand, the use of additional resistance in the voltage circuit and the effect of the short-circuited winding on the current electromagnet, renders the meter more sensitive to the effect of small variations in frequency and waveform. In consequence the accuracy is not so good when these disturbing factors are present.

8.11. Three-Phase Four-Wire Reactive Meters. Reactive meters for use on three-phase four-wire systems are similar, as regards the principles involved, to the three-phase three-wire reactive meters already described. They differ mainly in the fact that three elements are provided instead of two; the reasons for this are fairly obvious and are the same as are applicable to three-phase four-wire energy meters. In the circumstances it will not be necessary to describe in detail the many types which have been devised and it may suffice if the salient features only are referred to.

If the closest accuracy on unbalanced loads is desired three measuring elements are essential. Many meters have been made with two measuring elements only and on the current electromagnet of each, two current windings are provided. One current winding on one electromagnet is connected in the red line and one current winding on the

other electromagnet in the blue line; the two remaining current windings, one on each electromagnet, are joined in series and connected in the yellow line. Such an arrangement may be satisfactory provided that the line currents are balanced and the power-factor is the same in each. The chances however of obtaining unbalanced loads are greater in four-wire circuits, which frequently include single-phase loads such as lighting and heating, than in three-wire circuits which are mainly confined to power supplies in which a motor load predominates.

As in the case of three-phase three-wire reactive meters, the voltage elements are energized by voltages which lag 90 deg. (or 120 deg.) behind the voltage in the phase to which the associated current elements are connected; for this reason, all meters so constructed are dependent for their accuracy on the line voltages being reasonably balanced. This assumption is usually justified in a great measure and the amount of voltage unbalance experienced in practice is generally accepted as being of little importance.

Referring now to the three-phase three-wire three-element reactive meter described in Section 8.7., this meter can be used equally well on a four-wire circuit. The connections are as shown in Fig. 118, which remains unchanged, apart from the addition of the neutral conductor. No connection is made however, between the meter and the neutral and the accuracy of the measurement is not in any way affected; the meter registers at a rate proportional to $3 \times E \times I \times \sin \phi$, as pointed out on page 278. It is necessary to divide this by $\sqrt{3}$ in order to obtain the correct registration and the most convenient method of accomplishing this without calculation is to modify the gearing of the register so as to give a direct reading. Over a time inverval t, the meter will then register $\sqrt{3} \times E \times I \times t \times \sin \phi$ or $3 \times e \times I \times t \times \sin \phi$ which is the same thing.

An alternative arrangement which permits the meter to be constructed with voltage electromagnets wound for connection between line and neutral is shown in Fig. 126. Three auto-transformers are provided and are connected in delta to the three-phase supply; each auto-transformer has a tapping and between the tapping point and one of the line terminals, a voltage equal to the line to neutral voltage is obtainable. Thus, the voltage between R and R_1 is in phase with the voltage RY and is equal in magnitude to the voltage RN. By connecting the meter in the manner shown, it will register directly and without the use of a dividing-factor the quantity $3 \times e \times I \times t \times \sin \phi$. The vector diagram in Fig. 119 will apply equally to this arrangement.

Instead of delta-connected auto-transformers, a method which employs star-connected auto-transformers may be used. The connections

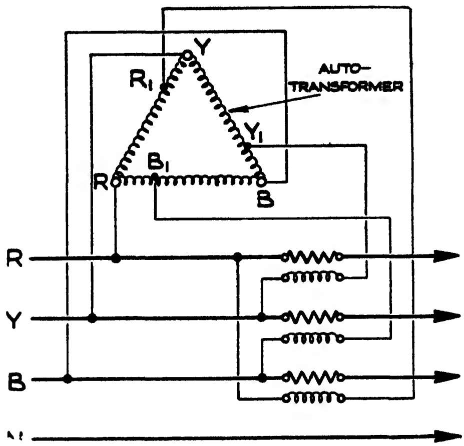


FIG. 126.—Three-phase four-wire reactive meter with auto-transformers connected in delta.

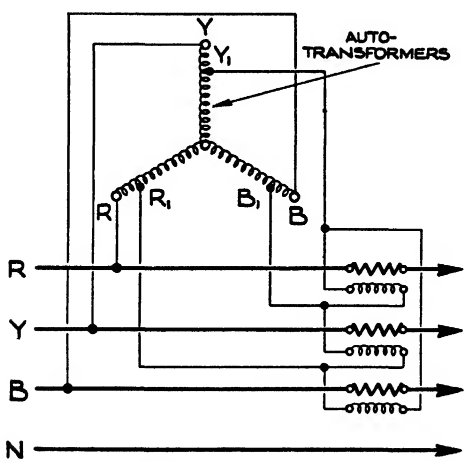


FIG. 127.—Three-phase four-wire reactive meter with auto-transformers connected in star.

are shown in Fig. 127 and as in the case of the delta connection, the meter will register directly and without the use of a dividing factor the quantity $3 \times e \times I \times t \times \sin \phi$. The voltage between any two tapping

points is equal to the voltage between any line and the neutral, when the voltages are balanced. For example, the voltage between R_1 and B_1 is in phase with the voltage across RB, and equal in magnitude to the voltage RN. The vector diagram in Fig. 119 applies also to this arrangement.

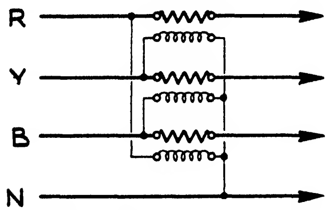


FIG. 128.—Three-phase four-wire reactive meter with internal phase compensation.

All the foregoing methods for the measurement of three-phase four-wire reactive component employ meter elements in which the voltage electromagnet flux lags 90 deg. behind the applied voltage. The three-phase three-wire internally compensated meter, having voltage electromagnet flux lagging 60 deg. behind applied voltage, may also be adapted to the measurement of four-wire reactive com-

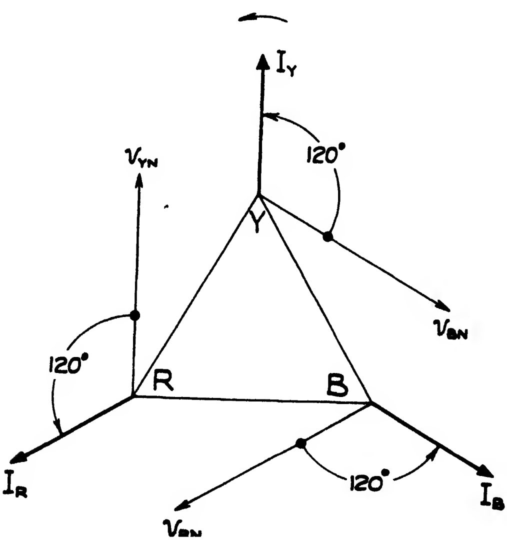


FIG. 129.—Vector diagram for three-phase four-wire internally compensated reactive meter.

ponent. A connection diagram for this adaptation is shown in Fig. 128 and as auto-transformers or the like are not required, the connections are of a very simple character. The vector diagram in Fig. 129 shows

the relationship between the voltages applied to the voltage electromagnets and the currents in the meter current coils when the power-factor of the loads is unity. With lagging currents the phase displacement between voltage and current vectors will be reduced, and at zero power-factor (lagging) they will be 30 deg. apart with the current vectors leading the voltage vectors in each case.

8.12. Reactive Meters in Interconnectors. The metering of reactive power in circuits where the direction of power flow is liable to reversal presents a little complication. A case in point arises where two or more power stations are interconnected and share the load between them. The power-factor at which one station operates is not necessarily the same as the other, nor the same as the power-factor of the load. A difference in voltage between one station and the other will result in a difference in power-factor, and at times the current in the interconnector may be leading. In addition there may also be change in the direction of power flow.

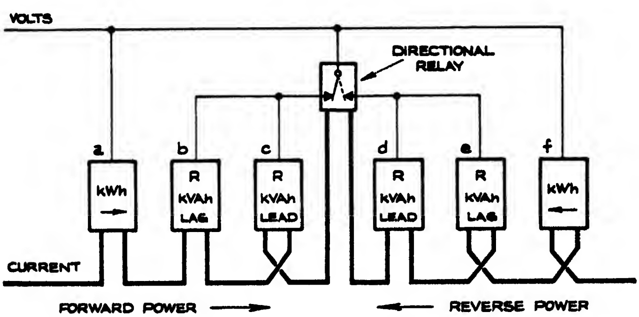


FIG. 130—Arrangement of meters for measuring active and reactive energy in circuit where power flow may be in either direction and current lagging or leading.

A reactive meter which registers in the forward direction when the current is lagging will register in the reverse direction when the current is leading, unless prevented by a ratchet and pawl device. The same condition will arise if the direction of power flow is reversed and since a reactive meter cannot discriminate between forward power with lagging current and reverse power with leading current, it becomes necessary to duplicate the meters where these conditions are likely to arise.

In order to deal satisfactorily with all the conditions in an interconnector, six meters and a directional relay are required. A single-line diagram showing the connections to these meters is given in Fig. 130.

The six meters comprise two for energy measurement, two reactive meters for lagging current and two reactive meters for leading current, together with a directional relay. Each meter is fitted with a ratchet and pawl to prevent reversal and all are connected in series in two sets of three each. Meters *a*, *b*, *c*, register forward power and *d*, *e*, *f*, register reverse power. The directional relay controls the voltage circuits of the reactive meters according to the direction of power flow. A little consideration will show that at any given instant two meters will be registering, two will be prevented from registering by the action of the ratchets and pawls, and the other two prevented from registering by the disconnection of their voltage circuits. Also, one of the meters which is registering will be an energy meter.

CHAPTER IX

KILOVOLT-AMPERE METERS

9.1. Influence of Power-Factor on Supply Costs. The cost of supplying electrical energy to industrial consumers depends not only on the kWh consumed but also on the power-factor of the load and the maximum demand. Where there is no power-factor tariff, the consumer who requires 100 kVAh at unity power-factor pays exactly the same price for current as the consumer who takes 200 kVAh at 0·5 power-factor. But the cost of the supply in the second case is higher than in the first. The I^2R losses in the transmission and distribution system and also in the generators and transformers are four times as great in supplying the consumer at 0·5 power-factor and the effective use which can be made of the supply system is less.

It has been computed that the average losses in this country due to units unaccounted for are of the order of 12 per cent., and a substantial part of these losses results from reactive power circulating in the supply system without doing useful work. The cost of these losses per kWh sold is comparable to the fuel cost per kWh. Any improvement which can be effected in the power-factor of the load will result in a lowering of the cost per kWh by reducing the I^2R losses in the supply system, and will enable capital expenditure locked up in cables and plant to be used more effectively, thus further reducing the all-in costs.

Since consumers having a load with a low power-factor incur losses which result in an increase in the average cost per kWh supplied, it does not appear equitable to expect consumers with a high power-factor to share these additional costs. Accordingly, tariffs have been devised whereby the charge to the consumer is related to the cost of the supply. One such tariff consists of two parts, the first being a fixed charge based upon the consumers' maximum demand in kVA, and the second, a running charge based upon the consumption in kWh. Under this tariff the consumer with a high power-factor will, other things being equal, incur a lower fixed charge than the consumer with a low power-factor, and the latter may, by the installation of devices for the improvement of power-factor, reduce his fixed charge. This is an encouragement to industrial users of electrical energy to improve their power-factor and thus to reduce the cost of the energy supplied.

9.2. Improvement of Low Power-Factor. Low power-factor in industrial installations is almost invariably due to lagging currents. This may be the result of running induction motors lightly loaded and therefore under inefficient conditions, or it may be due to the use of plant which has an inherently low power-factor. Correction for this undesirable condition is usually effected by the installation of static capacitors which take a leading current from the supply system, although other methods are also available. The improvement in the power-factor and the reduction in the kVA required, resulting from the installation of static capacitors or other power-factor-correcting equipment, may be seen from the vector diagram in Fig. 131 which is approximately to scale, and from a numerical example. A consumer with a load of 100 kW has a power-factor of 0·5 and consequently draws 200 kVA from the supply

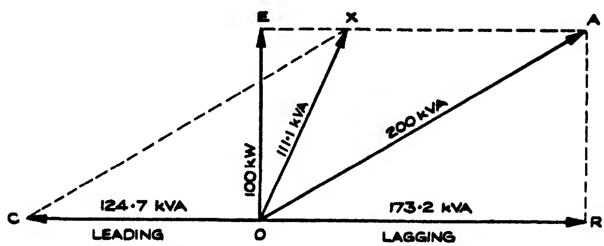


FIG. 131.—Reduction in kVA load by means of static capacitors.

system. It is desired to raise the power-factor to 0·9 by the installation of static capacitors.

In the diagram, the line *OE* represents the energy component of 100 kW which is in phase with the applied voltage, and *OA* the phase and magnitude of the load which is 200 kVA. As the power-factor is 0·5, *OA* is lagging 60 deg. behind *OE*. The reactive component *OR* is lagging 90 deg. behind the applied voltage and amounts to 173·2 kVA. A static capacitor rated at 124·7 kVA takes a current leading the applied voltage by 90 deg. and is represented by the vector *OC* in phase opposition to *OR*. The resultant of *OA* and *OC* is the line *OX*, equal to 111·1 kVA, this being the reduced kVA drawn from the supply, due to the improvement in the power-factor. It is not customary to raise the power-factor above 0·9 at the time of maximum demand, as the capital expenditure on corrective equipment is not justified by the reduction in the kVA maximum demand charges. Nevertheless, the power-factor will automatically improve as the load is reduced, if the capacitors

remain permanently in circuit and the power-factor will become unity when the reactive kVA (lagging) falls to the same magnitude as the kVA (leading), that is 124·7 kVA in the diagram. Any further reduction in the reactive kVA will result in a leading current being drawn from the supply, but this is of no importance as it can only occur at the time of light load and will not affect the indication of the kVA demand indicator.

9.3. Value of kVA-Hours. It is not usual for a supply authority to make a charge for the kVA-hours shown on the register, if any, fitted to the kVA meter; the sole function of the meter is to indicate the maximum demand in kVA and a little consideration will show that if the power-factor of the load varies from time to time, the record of kVA-hours shown on the register is meaningless. For example, assuming that the meter registers kVA-hours correctly at any power-factor, lagging or leading, the kVA-hours registered during an interval when the power-factor is unity will be equal to the kW-hours registered on an energy meter. Similarly, the kVA-hours registered during an interval when the hypothetical power-factor is zero, will be equal to the kVA-hours registered by a reactive meter. At an intermediate power-factor, the kVA-hours registered will be proportional to $\sqrt{(W^2 + Q^2)}$ where W is the registration on an energy meter and Q on a reactive meter, both connected in series with the kVA meter.

It will be obvious in these circumstances that the monetary value of the kVA-hours registered varies with the power-factor. At unity power-factor the registration represents useful energy supplied to the consumer, but at zero power-factor the consumer has received no useful energy and at intermediate power-factors there has been a variable proportion of useful energy in each kVA-hour registered. A purchaser of fruit may obtain 5 apples and 6 plums and 7 gooseberries, the sum of which amounts to 18 fruits. But if each variety of fruit has a different monetary value, it will not be possible to evaluate 18 fruits without knowing the proportions of each variety represented in the total. Similarly it is not possible to assign any definite value to the kVA-hours registered by a kVA meter during an interval when the power-factor is variable.

The demand indicator mechanism fitted to a kVA meter usually consists of a train of wheels terminating in an arbor carrying a large pointer associated with a scale, from which can be read the value of the maximum demand in kVA. The wheel train is driven by the meter rotor and provision is made for the periodical disconnection of the drive and

the restoration to zero of the driving mechanism. A time-switch or other time-controlled element determines the period, usually of thirty minutes' duration, during which the mechanism is driven forward; the pointer is fitted with a non-return device and remains in position when the driving mechanism is restored to zero. The pointer does not return and indicates the average value of kVA demand during the first time interval. During the next time interval the mechanism is again driven forward, but if the average load in the second interval has been no greater than in the first, the pointer will remain unmoved. In a succession of time intervals no further movement of the pointer will take place until there is an increase in the average value of the load, in which case the pointer will be advanced by the mechanism to a new position. At the end of the accounting period, which may be a month or a quarter, the position occupied by the pointer will be an indication of the maximum average load which has been experienced in any one of the successive time intervals since the last time the pointer was set to zero.

9.4. kVA Meter for Restricted Range of Power-Factor. One of the simplest forms of kVA meter is the type which is suitable for measuring kVA over a restricted range of power-factor, for use on a three-phase three-wire circuit. It consists of a two-element meter of conventional construction, but modified as regards the normal phase displacement between the voltage and current fluxes. Most manufacturers can supply this type of meter and as a rule two power-factor ranges are offered, the one covering the range between unity and 0·8 and the other the range between 0·9 and 0·5 power-factor. Within these ranges, the accuracy with which kVA demand can be measured is satisfactory for most ordinary commercial purposes, but substantial errors are incurred if the range for which the meter is adapted is exceeded.

The principle upon which this form of meter operates may be explained by considering in the first place the effect of change of power-factor, within a limited range, on the registration of an ordinary single-phase kWh meter. The voltage flux in this meter is normally adjusted to lag 90 deg. behind the voltage applied to the terminals of the voltage electromagnet, and if this adjustment is correctly made, the meter will register at a rate proportional to $E \times I \times \cos \phi$ where ϕ is the angle of phase displacement, lagging or leading, between the current I and the voltage E in the load circuit. Assuming that the error of the meter at unity power-factor is zero, the registration when the current lags or leads by 18 deg. will be proportional to $E \times I \times \cos 18°$. Reference to

trigonometrical tables gives cos 18° = 0·9511 or say 0·95 approximately. Accordingly the rate of registration when the current lags or leads 18° will be equal to $E \times I \times 0{\cdot}95$ or 95 per cent. of the registration at unity power-factor. Obviously this meter which registers at a rate proportional to the watts at any power-factor also registers at a rate approximately proportional to the volt-amperes over a range of power-factor between 0·95 lead to 0·95 lag; the actual error varying between 5 per cent. slow and zero. In other words, a kWh meter can be used to register kVA hours over a limited range of power-factor without incurring a large error. By adjusting the meter to register 2·5 per cent. fast at unity power-factor, the maximum error will be halved and the meter will then register at a a rate proportional to the volt-amperes

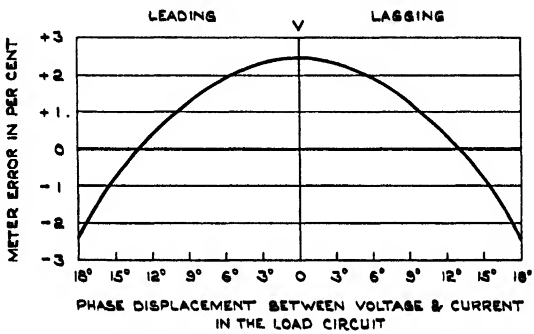


FIG. 132.—Error curve for kVA meter in which voltage flux lags 90 deg. behind applied voltage.

within $\pm$ 2·5 per cent. between 0·95 power-factor leading and 0·95 power-factor lagging. The actual error in kVA measurement at various angles of phase displacement, using an ordinary kWh meter which is adjusted to be 2·5 per cent. fast at unity power-factor is shown in Fig. 132.

9.5. kVA Meter for Power-Factor Range of Unity to 0·8 Lag. In practice it is very unlikely that the power-factor of an industrial load will vary between the limits of 0·95 lead and 0·95 lag, at any rate at the time of maximum demand. The curve in Fig. 132 relates to a meter in which the flux due to the voltage electromagnet lags 90 deg. behind the applied voltage and it shows that the error in measuring kVA does not exceed $\pm$ 2·5 per cent. when the load current is displaced within a range of $\pm$ 18 deg. with respect to the applied voltage. If now the flux due to the voltage electromagnet is caused to lag by an additional angle θ with

reference to the current electromagnet flux, when the power-factor of the load is unity, the meter will measure kVA within similar limits of error but over a different range of power-factor depending upon the value assigned to θ.

The registration of such a meter at any power-factor is proportional to $E \times I \times \cos(\phi - \theta)$ where ϕ is the angle of lag of current behind voltage in the load circuit, and θ is the additional angle of lag of voltage flux, beyond the 90 deg. which is normal to a kWh meter. If θ is made equal to 18 deg., the registration of the meter will be proportional to $E \times I \times \cos(\phi - 18°)$. The maximum rate of registration will occur when $\phi = \theta$, that is, when the load current lags by an angle equal to the additional angle of lag of the voltage flux. The curve in Fig. 132 will

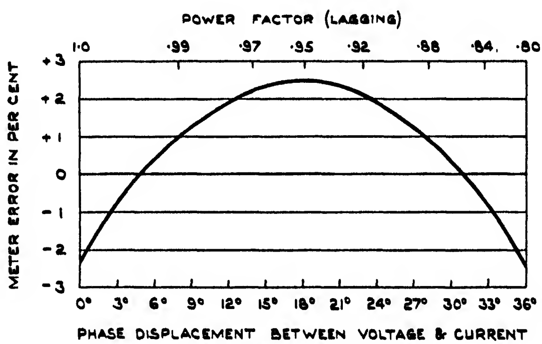


FIG. 133.—Error for kVA meter covering power-factor range unity to 0·8.

again represent the meter errors over a range of power-factor corresponding to $\pm$ 18 deg. but the centre line OV will be displaced 18 deg. to the left. The altered conditions are shown in Fig. 133 and it will be noted that the meter now covers the range between 0 deg. and 36 deg. lagging current in the load circuit; the minimum rate of registration occurs at the extremities of the range corresponding to power-factors of unity and 0·8 respectively.

The method usually adopted to obtain the additional 18 deg. lag in the voltage flux is to fit an extra-heavy copper loop on the voltage electromagnet in place of that used for the normal quadrature adjustment; the voltage flux will then lag 108 deg. behind the applied voltage when the adjustment is correctly made. A meter for use on a three-phase three-wire circuit will have two such single-phase elements and

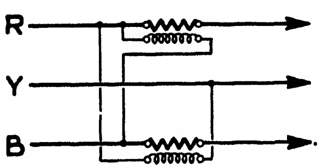
on a four-wire circuit will have three elements. The connections to the supply are exactly the same as for corresponding kWh meters, but it should be noted that whereas incorrect phase sequence has little effect on the accuracy of most kWh meters, correct phase sequence is essential in connecting up kVA meters. Failure to observe this rule will result in large errors, the magnitude of which will depend upon the power-factor of the load.

9.6. kVA Meter for Power-Factor Range of 0·9 to 0·5. The power-factor of an average industrial load *at the time of maximum demand*, which latter is the only time that matters in kVA metering, does not as a rule lie within the limits between unity and 0·8 unless power-factor improving equipment is installed. If follows therefore, that the meter already referred to is not suitable for the measurement of kVA demand in such a case. An alternative form of meter, suitable for a range of power-factor between 0·9 and 0·5 is preferable for the average industrial load, as the power-factor *at the time of maximum demand* is almost certain to lie between these limits. It is most unlikely when the installation is carrying its maximum load, consisting usually of induction motors, lighting equipment and possibly electric heating devices, that the power-factor will be below 0·5. It is equally unlikely with a mixed load such as the foregoing that the power-factor will be higher than 0·9 unless there are some special circumstances. It is quite true that a power-factor below 0·5 may be experienced, but if so, this will occur at the time of light load and consequently is of no importance as it cannot influence the indication of the maximum-demand indicator. It is equally true that under no conditions, either light load or otherwise, is the power-factor likely to be higher than 0·9 in the circumstances now being considered.

A kVA meter suitable for covering the range of power-factor between 0·9 and 0·5 is made on a somewhat similar principle to that already described for the range between unity and 0·8. The lag of voltage flux behind the voltage normally applied to the voltage electromagnet is increased by 43 deg. as compared with 18 deg. in the unity to 0·8 power-factor range meter. It is not practicable to lag the voltage flux by so large an amount as an additional 43 deg. by means of a copper band or quadrature loop on the voltage electromagnet and other means must be adopted in this instance.

The most usual method is to connect the voltage electromagnet to another phase of the supply, lagging as nearly as possible by the desired amount, and then to make the necessary final adjustment by

other means. In this case the voltage electromagnet is connected to a phase which is already lagging 60 deg. behind that normally applied to a kWh meter. This will be made clear from examination of the connection diagrams in Fig. 134 (a) and (b) which relate to three-phase three-wire and three-phase four-wire kVA meters respectively. These diagrams should be compared with corresponding diagrams relating to three-phase three-wire and three-phase four-wire kWh meters as shown in Figs. 95 and 98. It may be noted in the case of Fig. 134 (b) relating to a three-phase four-wire kVA meter, that the voltage coils are connected to phases leading by 120 deg. as compared with the kWh meter connections, but by reversal of the connections to the coils, equivalent to turning them through 180 deg. electrically this becomes a 60 deg. lag in phase.



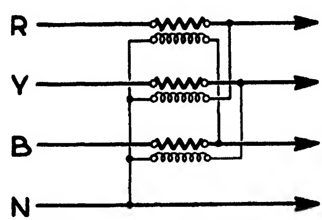


Fig. 134.—Connections for kVA meter covering power-factor range 0·9 to 0·5.
(a) Three-phase three-wire meter.
(b) Three-phase four-wire meter.

The additional 60 deg. lag in voltage flux resulting from these modified connections is more than is required and the angle is reduced to 43 deg. by artificially lagging the current flux due to the current electromagnet. Where the current electromagnet consists of a ⊔-shaped iron core, rectangular copper tubes closely embracing the two poles are usually employed for this purpose. The current coils are wound over the copper tubes, which are so proportioned that the current induced therein by the passage of the main current, displaces the current flux by approximately 17 deg. in the lagging direction. Since the voltage flux has been lagged by 60 deg. and the current flux by 17 deg., the relative phase displacement is reduced to 60 deg. − 17 deg. = 43 deg. which is the desired amount.

It is not possible as a rule to proportion the copper tubes so as to give exactly 17 deg. lag in current flux, but any small discrepancy can be corrected by adjustment of the quadrature loop on the voltage electromagnet as is normally employed in the case of the inductive load

adjustment on a kWh meter. Some manufacturers find it more convenient to insert a resistance in series with the winding of the voltage electromagnet for the purpose of reducing the lag of the voltage flux, instead of lagging the current flux. This method is equally effective, but is liable to influence the error of the meter if subjected to variation in frequency of supply or to variation in waveform.

The curve in Fig. 135 shows the variation in the error of the meter due to variation in phase displacement between voltage and current in the load circuit. This curve is similar to that for a unity to 0·8 power-factor range meter, but shows that the maximum error between 0·9 and 0·5 power-factor lies between the limits of $\pm$ 2·2 per cent. The

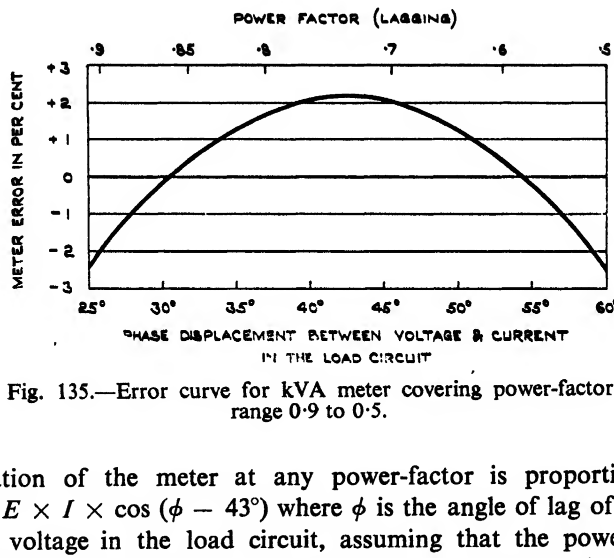


Fig. 135.—Error curve for kVA meter covering power-factor range 0·9 to 0·5.

registration of the meter at any power-factor is proportional to $\sqrt{3} \times E \times I \times \cos(\phi - 43°)$ where ϕ is the angle of lag of current behind voltage in the load circuit, assuming that the power-factor is the same in each phase. The maximum rate of registration occurs when $\phi = 43$ deg. at which point the registration would be equal to $\sqrt{3} \times E \times I \times \cos(43° - 43°) = \sqrt{3} \times E \times I$. As the meter is intended for a total variation of 34 deg. in the angle of lag ϕ in the load circuit, the minimum rate of registration will be at the extremities of this range and will correspond to 43 deg. $\pm$ 17 deg. = 26 deg. and 60 deg. These extremes occur at power-factors proportional to cos 26 deg. and cos 60 deg. or 0·8988 (say 0·9) and 0·5 respectively. If the meter is adjusted to register $\sqrt{3} \times E \times I$ correctly at 43 deg. lag, it will register 95·6 per cent. of the correct amount, that is 4·4 per cent. slow

at the extremities of its range, but by setting the meter to register 2·2 per cent. fast at 43 deg. lag, it will register 2·2 per cent. slow at 26 deg. and 60 deg. lag respectively. Thus, the error in the measurement of kVA maximum demand will not exceed $\pm$ 2·2 per cent. in addition to the normal meter error within the range of power-factor between 0·9 and 0·5.

9.7. kVA Meter for Power-Factor Range of Unity to Zero. In previous paragraphs it has been stated that the sum of the kVA-hours shown on the register of a kVA meter is a meaningless quantity if, during the period in which the registration occurred, there has been any variation in power-factor. The sole purpose of a kVA meter is to give an indication of the maximum demand averaged over a predetermined time interval, which latter may be as short as 15 minutes or as long as 60 minutes. In this country the time interval usually selected is 30 minutes and it may be presumed that the power-factor during the time of maximum demand will not vary over a wide range. It is not always possible to state with certainty that the power-factor will be within defined limits when the maximum demand occurs and to cover such cases kVA meters have been designed which are correct over a wider range of power-factor than the restricted range instruments already described.

One kilo-volt-ampere meter in this class is manufactured by Landis and Gyr and is known by the registered name of "Trivector". It consists of two meters in one case, the one arranged to measure the energy component in kWh and the other to measure the reactive component in kVARh. Each meter has its own register and in addition a third register is provided which records the total kVAh. This third register is associated with a scale and pointer, giving an indication of the maximum demand in kVA during a succession of predetermined time intervals. The meter makes use of the principles incorporated in the restricted range kVA meter and by means of an ingenious mechanism covers the whole range of power-factor from unity to zero in a succession of steps. By restricting the range of power-factor over which the meter is operative in each step to the equivalent of $\pm$ 11¼ deg., as compared with the $\pm$ 17 deg. or $\pm$ 18 deg. in the meters already described, the variation in the error of the meter can be reduced to $\pm$ 1 per cent. approximately.

The means whereby this is accomplished is shown in a skeleton diagram in Fig. 136. The rotor of a kWh meter adjacent to a kWh register may be seen in the upper left-hand corner of the diagram, and the rotor of a reáctive kVAh meter with corresponding register in the

lower left-hand corner. A horizontal shaft driven by the rotor of the kWh meter extends to the right and drives through a ratchet coupling and a pair of bevel wheels 1, on to a vertical spindle carrying at its lower extremity, a kVAh register. A second horizontal shaft driven by the rotor of the reactive kVAh meter drives in a similar manner through a pair of bevel wheels 5, on to the vertical spindle.

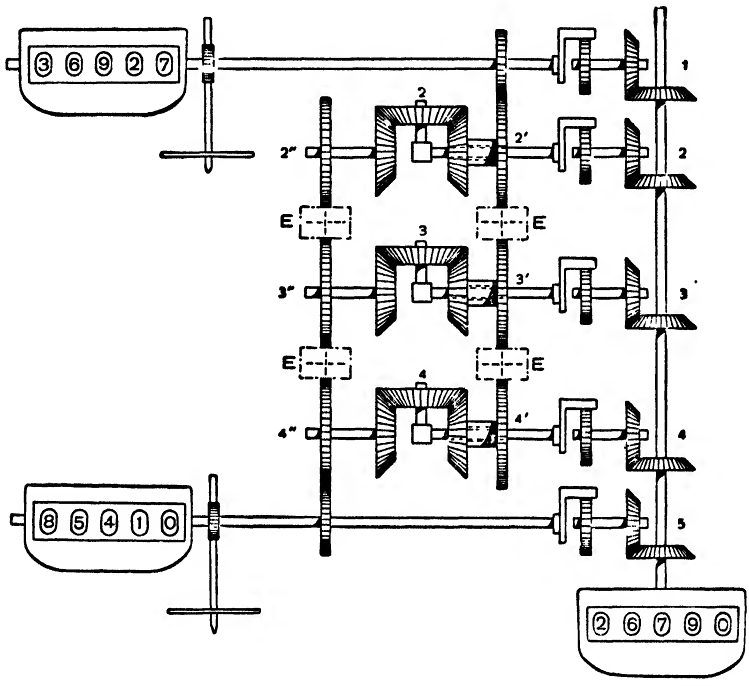


FIG. 136.—Arrangement of gearing for kVA measurement in Landis & Gyr Trivector meter.

Three differential gears at 2, 3, 4, each comprising two sun wheels and a planet wheel, are mounted on parallel shafts and coupled together through intermediate gearing as at *E*. All the right-hand sun wheels are driven by the kWh meter and all the left-hand sun wheels by the reactive meter. The planet wheel in each differential sums up the movement communicated to the two sun wheels and transfers it through ratchet couplings and pairs of bevel wheels at 2, 3, 4, to the vertical spindle. Thus, the vertical spindle which rotates at a speed proportional

to the load in kVA, has motion communicated to it through five ratchet couplings and five pairs of bevel wheels, and may be regarded as a totalizator.

The relative speeds of the meter rotors will vary according to the power-factor of the load. When the power-factor is unity the whole of the registration on the kVAh register is derived from the kWh meter, as the reactive meter is stationary. When the power-factor is zero, the whole of the registration is derived from the reactive meter and the kWh meter is stationary. At intermediate power-factors both meters register, the kWh meter being the faster of the two at power-factors between unity and 0·707, and the reactive meter the faster at power-factors below this value. At 0·707 power-factor, corresponding to 45 deg. lag in current, both meters register at the same rate.

The object of the differentials is to obtain the sum of the registrations of the two meters in varying proportions and to pass on these registrations to the totalizator spindle through the ratchet couplings and bevel gears. The totalizator spindle is driven by the fastest moving ratchet coupling at any given instant, and this will be determined by the power-factor of the load. If the power-factor is varied progressively (as can be done under test conditions) from unity to zero, the drive to the totalizator spindle will be communicated through one of the bevel gears 1, 2, 3, 4 or 5, and in that order. Generally speaking, only one ratchet coupling will be driving at any selected instant, except when the power-factor is passing through certain values, in which case two will be running at the same speed. It will be appreciated that, while five

TABLE 8

Portion of Gearing utilized to drive Demand Indicator in "Trivector" Meter over Various Ranges of Power-Factor

Angle of lag of current	Range of power-factor	kVA Demand Indicator is driven by—
0° to 11¼°	Unity to 0·981	kWh meter and bevel wheels 1
11¼° „ 33¾°	0·981 „ 0·832	Differential 2 „ „ „ 2
33¾° „ 56¼°	0·832 „ 0·556	„ 3 „ „ „ 3
56¼° „ 78¾°	0·556 „ 0·195	„ 4 „ „ „ 4
78¾° „ 90°	0·195 „ Zero	kVARh meter „ „ „ 5

separate channels exist for transmitting motion from meters to totalizator spindle and kVA maximum demand indicator, four of these channels are running idle at all times except at the transition points. The path utilized to transmit movement from the meters to the demand indicator at various power-factors can be followed by reference to Table 8.

The variation in the error of the kVAh register at various power-factors, assuming that the kWh meter and the reactive meter have no inherent errors, is shown by the curve in Fig. 137. That portion of the curve between 0 deg. and 11¼ deg. represents the rate of registration contributed by the kWh meter when driving directly on to the totalizator spindle; at the other extremity, that portion of the curve between 78¾ deg. and 90 deg. is contributed solely by the kVARh meter. The three humps between these extremities show the range covered by one or another of the three differentials. The points at the base of the four

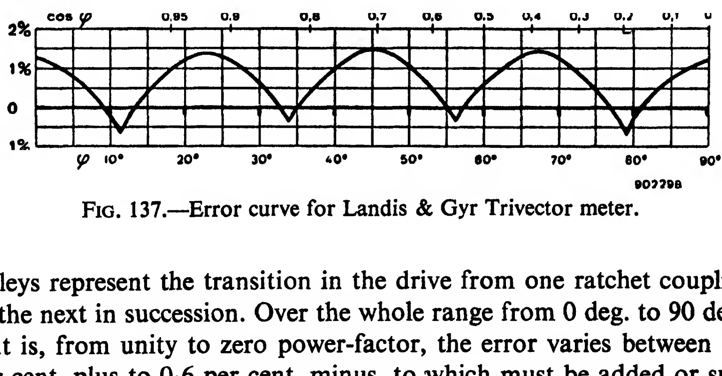


FIG. 137.—Error curve for Landis & Gyr Trivector meter.

valleys represent the transition in the drive from one ratchet coupling to the next in succession. Over the whole range from 0 deg. to 90 deg., that is, from unity to zero power-factor, the error varies between 1·5 per cent. plus to 0·6 per cent. minus, to which must be added or subtracted the error of the meters at the particular load on which they are operating. The employment of a large number of differential gears in the manner described would render possible the measurement of kVAh with negligible error at all power-factors. The mechanical complexity of such an arrangement would however, be undesirable and the compromise which has been adopted more than covers all practical requirements.

It will be seen that if the maximum demand should occur when the power-factor of the load is in the region of zero (a very unlikely contingency), the meter is equipped to register this. Provision can also be made for the measurement of maximum demand when the power-factor varies between zero leading and unity, (an equally unlikely

contingency under normal working conditions). It has already been pointed out that a reactive meter will reverse its direction of registration if the current assumes a leading value, and this would result in the differentials totalling the difference instead of the sum of the kWh and kVARh registrations. Accordingly, a relay may be connected in the circuit in such a manner that, when a leading current occurs, the polarity of the voltage elements of the reactive meter is reversed, thus restoring the registration of this meter to the forward direction.

9.8. kVA Meter with Spherical Integrator. A kVA meter made in America by the Westinghouse Company and known as Type RI, combines with a kWh element and a kVARh element, a mechanical integrating device which gives the vector sum of the registrations of the two.

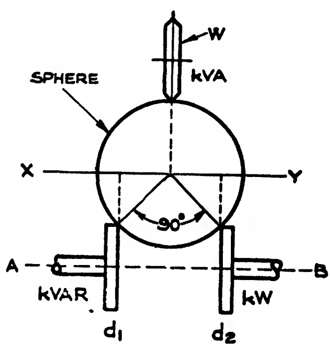


FIG. 138.—Spherical integrating mechanism for kVA meter.

It is suitable for use on any power-factor between zero lagging and unity and for leading power-factors over any range likely to be experienced under working conditions. It consists essentially of a light aluminium sphere supported on two wheels driven respectively by the kWh and kVARh meters. A third wheel communicates motion from the sphere to a register which gives a record of the total kVAh. The average demand is measured over fifteen-minute intervals, and is recorded on a chart, from which the maximum demand in kVA can be ascertained.

The basic features of the integrating mechanism are shown in Fig. 138. Two coaxial shafts arranged horizontally on an axis *A B* carry on their adjacent extremities two parallel discs d_1 d_2 which are in frictional engagement with the aluminium sphere resting thereon. The disc d_1 is driven by the reactive meter and d_2 by the energy meter; the points of

contact between the edges of the discs and the sphere are separated by 90 deg. of the circumference of the latter. The sphere revolves on an axis XY in the plane of the paper, the position of the axis being dependent on the relative speeds of the discs d_1 d_2, which in turn are dependent upon the power-factor of the load. When the load current is lagging 45 deg., corresponding to a power-factor of 0·707, both discs will rotate at the same speed and in the same direction. The XY axis under this condition will lie parallel to the axis of d_1 d_2 as shown in Fig. 138.

A bracket capable of rotation about an imaginary line passing through the centre of the sphere carries a wheel W which rests on and is driven by the sphere: this bracket and wheel are shown in side elevation

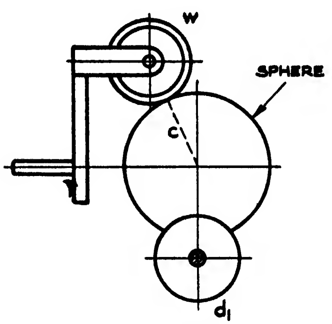


FIG. 139.—Side view of spherical integrating mechanism.

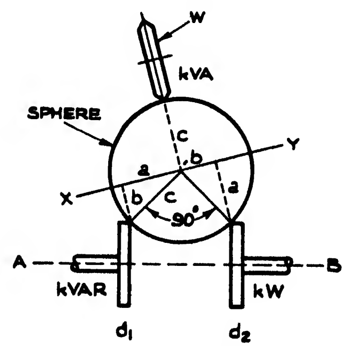


FIG. 140.—Position of spherical integrating mechanism at high power-factor.

in Fig. 139 and the axis of the wheel is parallel to the XY axis. The wheel itself is positioned on its axis in line with the centre of the sphere so that the line of contact between the wheel and the circumference of the sphere is along a diameter. At power-factors higher than 0·707, the XY axis will be inclined so that the wheel W occupies a position to the left of a vertical line passing through the centre of the sphere as shown in Fig. 140. At power-factors lower than 0·707 the wheel W will be to the right of the said vertical line.

Under steady load conditions the points of contact between the sphere and the wheels d_1 d_2 and W will respectively lie on circles around the sphere. Each of these circles encloses a plane at right-angles to the XY axis. The dotted lines a, b, c in Fig. 140 indicate the radii of these circles. The radius a of the circle produced by the movement of the

kWh meter disc is proportional to the load in kW, that is $\sqrt{3} \times E \times I \times \cos\phi$. The radius b of the circle produced by the movement of the kVARh meter disc is proportional to the reactive power, that is $\sqrt{3} \times E \times I \times \sin\phi$. The radius of the circle followed by the wheel W is the radius of the sphere. From the geometry of the figure it will be seen that $c^2 = a^2 + b^2$ and $c = \sqrt{(a^2 + b^2)}$. It follows therefore, that the register which is driven by the wheel W advances by an amount proportional to the square root of the sum of the squares of the advances made by the kWh and kVARh meters. In other words the rate of movement of the wheel W is proportional to the true kVA in the circuit to which the meter is connected and the meter differs in this respect from the kVA meters previously referred to, in that the latter register only a more or less close approximation. On the other hand any slip which may occur between the driving or driven wheels and the sphere, or any mechanical imperfections in the mechanism, will detract from its accuracy and may well result in errors comparable in magnitude to the errors of approximation in other devices.

It is of interest to note that at unity power-factor the only source of motion contributed to the sphere is from the disc d_2 driven by the kWh meter. Under this condition the sphere pivots about the point of contact with the stationary disc d_1. The XY axis assumes an inclination of 45 deg. and the wheel W lies in the upper left-hand quadrant. The disc d_2 will drive on to the same circle around the circumference of the sphere as is traversed by the wheel W at the opposite point on its diameter. The kVAh register should show exactly the same advance as the kWh register if no slip takes place. Similarly at zero power-factor lagging, the disc d_1 alone will drive the sphere and the wheel W will be in the upper right-hand quadrant. The kVAh register will now show the same advance as the kVARh register. With a leading power-factor, the disc d_1 driven by the reactive meter will reverse in direction with the result that the XY axis will tend to become vertical, with the wheel W approaching a position on the extreme left. No relay or other auxiliary device is necessary for the purpose of altering the direction of rotation of the reactive meter element and the meter will still register kVA correctly under this condition.

9.9. kVA Meter with Shaded-Pole Driving Elements. The kVA meters described in previous paragraphs have all been provided with driving elements incorporating one or more voltage and current electromagnets, the magnetic fluxes of which have interacted to produce a driving-torque in the rotor. The type now to be described differs from the

foregoing in that the driving element has a current electromagnet only; this instrument is known as the Hill-Shotter kVA Maximum Demand Indicator and is manufactured by the Aron Electricity Meter, Ltd. The three-phase instrument, which is the one commonly used, has three separate measuring elements and is suitable for use on three-phase three-wire or four-wire circuits. It is also made with two elements for two-phase and one element for single-phase circuits. Two patterns of this meter are supplied, the first being what is described as the "declared voltage" pattern and the second as the "voltage compensated" pattern.

The declared voltage pattern kVA meter is actually the equivalent of an alternating current ampere-hour meter calibrated for use on a declared voltage. The assumption is made that the voltage of the supply during the interval in which the maximum demand occurs will in fact be equal to the declared voltage for which the instrument is calibrated. It is well-known that direct-current ampere-hour meters are used in many countries which are calibrated for use at a declared voltage. This practice has much justification and it may be assumed by some that a demand indicator is a parallel case. But such an assumption would be incorrect: an ampere-hour meter operates throughout its working life at a voltage which may fluctuate up and down within certain limits, but the tendency will be to average out the errors which result from these variations. A demand indicator on the other hand gives an indication of the maximum load which in all probability has occurred once only between consecutive monthly or quarterly readings. If in the particular time interval (say thirty minutes), during which the maximum load occurred, the average value of the voltage was high or low compared with the declared voltage the indication would be in error to a corresponding extent.

The Hill-Shotter kVA meter comprises a rotating element, a permanent magnet brake and one, two, or three driving electromagnets according to whether it is constructed for use on single, two, or three-phase systems; a maximum-demand indicator is driven by the rotating element. The description which follows applies to the three-phase instrument. The rotor consists of two aluminium discs mounted on a vertical spindle and supported between top and bottom bearings in a cast metal frame. Three driving electromagnets are attached to the frame and so disposed that one operates on the upper disc and the other two on opposite sides of the lower disc. The arrangement of a driving electromagnet is shown in Fig. 141. A rectangular laminated

iron core carries a current winding on the lower horizontal limb. Bifurcated pole pieces, between which the disc revolves, have copper shading rings on the outer extremities. The shading rings are adjustable in order to vary the driving torque, and across the airgap a magnetic shunt having a micrometer adjusting screw J permits a fine adjustment of torque to be made when balancing one element against another. A permanent magnet, between the poles of which the upper disc revolves, acts as a brake on the rotor and is carried on a supporting bracket. The position of the magnet is adjustable in order to vary the braking effect and a micrometer screw is provided for the purpose of

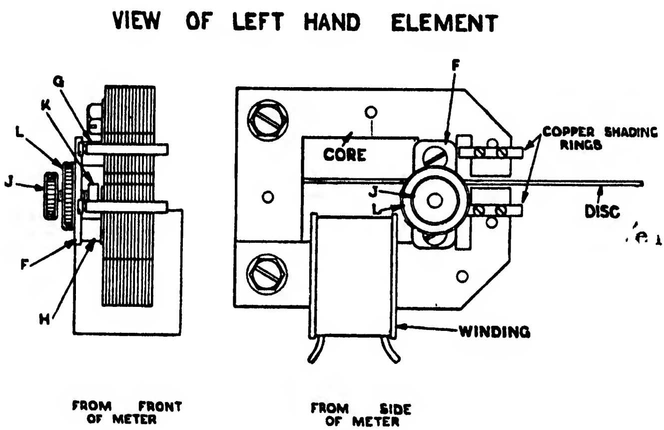


FIG. 141.—Driving electromagnet in Hill-Shotter kVA meter, declared-voltage pattern.

fine adjustment. The demand indicator driven by the rotor is scaled to indicate the maximum demand in kVA at the declared voltage of the supply to which the instrument is connected.

The principle on which the instrument operates is as follows: the three electromagnets are connected in the three lines of the supply system and when energized by the line currents each sets up a torque in the rotor, substantially proportional to the current in the winding. The speed of the rotor resulting from this driving force is determined in part by the permanent magnet brake. The magnetic flux set up in the driving electromagnets provides a supplementary braking effort varying as the square of the current; the two constituent braking efforts are arranged to be equal at full load and at high loads the meter has

substantially a straight-line characteristic. This is reflected in the graduations of the demand indicator scale, which are uniformly spaced at the upper extremity. Since this straight-line characteristic does not apply throughout the whole range of measurement, the instrument cannot be used to register the total kVA hours over a period of time, consequently no registering mechanism for such is provided. This omission however is of little importance, since the term "kVA hours" is meaningless unless supplemented by the value of the power-factor at which they are measured.

All the kVA meters to which reference has already been made measure the vector sum of the currents in the lines of a three-phase system; unlike these, the Hill-Shotter kVA meter measures the arithmetic sum of the line currents. Because of this fundamental difference, this meter will indicate a higher value of kVA than the other types if the line currents are unbalanced or if the power-factor is not the same in each phase. The justification claimed for this fundamental difference in performance is referred to later in this chapter. In transformer-operated instruments on three-phase three-wire circuits, it is very desirable to use three current transformers, that is, one for each element. As is well known the secondaries of two current transformers can be so connected as to reproduce in a third circuit the equivalent of the secondary current from a third transformer. The method however, involves some complication and is not recommended by the manufacturers of the meter except in cases where it is impracticable to instal the third transformer. On three-phase four-wire circuits the three line currents are not related in this manner and there is no alternative to the use of three transformers.

The limits of error guaranteed by the manufacturers of this instrument are as follows: From full scale down to one-third scale, plus or minus two per cent.; below one-third scale down to the lowest scale marking (about one-tenth of full scale), within plus or minus one per cent. of the full-scale marking; these limits apply at any power-factor and to balanced loads. They also apply to unbalanced loads with the following limitation: the instrument operates within the above limits of error so long as, at times of maximum load, the current in each one of the three phases does not differ from the mean value of the currents in the two remaining phases by more than 50 per cent. of that mean value. For more extreme conditions of unbalance, which are comparatively rarely encountered in practice, the use of single-phase instruments, one in each phase, is recommended.

The Hill-Shotter voltage-compensated pattern kVA maximum demand indicator differs from the declared voltage pattern in that provision is made for increasing or decreasing the torque of each driving-element, proportionally to any increase or decrease in the voltage of the phase to which the element is connected. The voltage range over which this compensation is effective is 12½ per cent. above or below the nominal voltage for which the instrument is constructed. The constructional features of the instrument are similar to those incorporated

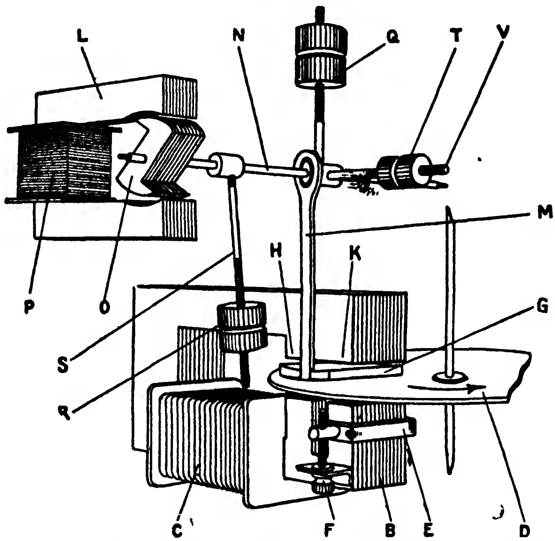


FIG. 142.—Driving electromagnet in Hill-Shotter kVA meter, voltage-compensated pattern.

in the declared-voltage pattern but each current electromagnet is associated with a voltage electromagnet which provides the voltage compensation.

The general arrangement of each driving element is shown in Fig. 142. The current electromagnet is substantially the same as that shown in Fig. 141, but the airgap in which the rotor disc revolves is wider, to permit the insertion of a swinging copper vane G suspended from a shaft N. An electromagnet consisting of a laminated core L energized by a voltage coil P has an armature O pivoted between the polar extensions and carried by the shaft N. Balance weights Q, R, T permit of adjustment to the position of the vane G in the airgap of the current

electromagnet B. The voltage coil P is energized between the neutral and the same line as that in which the current coil C is connected. The position of the vane G in the airgap depends upon the voltage applied to the coil P and the effect of the vane is to reduce the torque exerted on the rotor by the current electromagnet when the system voltage is below normal. Conversely, when the system voltage is above normal the vane swings into such a position that the torque produced by the current electromagnet is increased by an appropriate amount. It will be clear that the total torque exerted on the rotor is only dependent upon the magnitudes of the voltage and current and not on their phase relationships and consequently the indications are independent of power-factor. Since the position of the vane G is subject to gravitational control it is important that the instrument shall be correctly levelled when tested or installed. To facilitate this levelling, a plumb-bob, visible from outside the case, is fitted in every instrument.

9.10. kVA Meters of Various Types. Apart from the kVA meters already described, many other types have been suggested and a few have been produced commercially. Of these, some are too complicated or too expensive to survive in a competitive world and others have not fulfilled the expectations of their designers from the standpoint of performance. One prolific source of inspiration to would-be inventors of kVA meters has been the metallic rectifier, either copper-oxide or selenium, combined with some form of direct-current ampere-hour or watt-hour meter. So far as the author is aware, no successful kVA meter has been produced by this combination. A rectified current consists of a succession of half-waves all acting in the same direction. The same applies to a rectified voltage and consequently, the effects of phase displacement between current and voltage on the alternating-current side still persist on the direct-current side, as the peaks of the pulses do not coincide. The introduction of smoothing devices can minimize this effect and conceivably a single-phase kVA meter may be devised which is capable of giving an acceptable performance at a comparatively high cost. But single-phase kVA meters are not required in practical working and a three-phase instrument consisting of the combination of three direct-current watt-hour meters, complete with six rectifiers, smoothing devices, transformers and the associated means for summating the three registrations on one register and demand indicator becomes so costly and bulky as to be out of the question so far as commercial metering is concerned.

Another form of kVA meter which recently has been produced

commercially on a comparatively small scale, consists of a polyphase meter of conventional pattern, combined with a form of phase-shifter and a power-factor relay. The phase-shifter is connected to the three-phase supply and has a large number of tappings brought out to contact studs arranged in a circle. A rotary shaft driven by a motor and a step-by-step mechanism, carries four contact blades which are arranged to sweep over the contact studs. From the contact blades, connections are taken to the voltage coils of a polyphase meter and a power-factor relay. The latter is so arranged that, so long as the voltage and current applied to its voltage and current windings respectively, are in phase, the relay contacts remain open. If there is an alteration in the power-factor of the main circuit there will be introduced a phase displacement between the voltage and current applied to the coils of the power-factor relay. This produces a torque and results in the closure of a pair of contacts in the relay, which in turn starts up the motor and causes the rotary shaft to transfer the contact blades to another set of contact studs.

The voltage derived from the phase-shifter is constant in magnitude if the line voltage is constant, but there is a difference of approximately 10 deg. in phase between adjacent studs. When the contact blades reach a set of studs from which the derived voltage differs by less than 10 deg. in phase displacement from the phase of the current, the power-factor relay contacts open and the motor driving the rotary shaft stops. By this means the voltage applied to the relay and also to the meter is always maintained substantially in phase with the current in the main circuit. The motor which moves the contact blades is reversible, and the direction in which it moves is determined by the power-factor relay; this latter closes one pair of contacts if the current is leading with respect to the voltage across the relay and another set if the current is lagging. Thus, the motor is always caused to move in such a direction as to reduce the phase displacement between the voltage and current applied to the relay windings. By these means the polyphase meter is always working under conditions approximating to unity power-factor in the main circuit. The error in the kVA measurement resulting from this small departure from the ideal condition does not exceed plus or minus 0·75 per cent. above the normal meter error when measuring kWh.

In addition to the meters already described, which give a measurement of kVA derived from the integration of kVAh, there is another class of kVA maximum demand indicator operating on a thermal

basis. Most of these instruments measure current values only and are calibrated for use at a declared voltage. A few, however, are influenced by voltage as well as current. Again, the majority are for use on single-phase circuits, although one or two exceptions are constructed for poly-phase work. As this class is intended solely for the measurement of maximum demand and does not integrate kVAh, it is dealt with in the chapter relating to maximum demand indicators.

9.11. Ambiguities in the Measurement of kVA. A number of kVA meters have been described in the preceding paragraphs and reference has been made to the fact that in some cases the measurement of kVA demand is made by taking the vector sum of the volt-ampere-hours over an interval of time and in another case the arithmetic sum is taken. It is desirable when installing a kVA meter that some consideration should be given as to the quantity which the meter purports to measure and also to the factors which give rise to differences in the indications of the various instruments under different working conditions. Where the metering of large amounts of energy is undertaken it is not unusual for the consumer to instal his own check metering, in order to verify the accuracy of the charges made by the supply authority. In such a case both main and check meter should conform to the same definition of the quantity being measured if disputes are to be avoided.

According to the elementary principles involved in the measurement of power in a single-phase circuit the total current may be separated into two components, vectorially 90 deg. apart, the first being the power or watt component and the second the reactive or wattless component. These quantities are represented by the right-angled triangle *EOR* in Fig. 143. The line *OE* represents the true watts expended in the circuit and *OR* the reactive or wattless power. The hypotenuse *ER* represents the apparent watts or the volt-amperes and ϕ is the angle between the hypotenuse and the base of the triangle. If instantaneous values are taken, the following relationships exist between these quantities:

$$(1) \quad \frac{\text{kVAR}}{\text{kW}} = \frac{\text{OR}}{\text{OE}} = \tan \phi$$

$$(2) \quad \frac{\text{kVAR}}{\text{kVA}} = \frac{\text{OR}}{\text{ER}} = \sin \phi$$

$$(3) \quad \frac{\text{kW}}{\text{kVA}} = \frac{\text{OE}}{\text{ER}} = \cos \phi$$

From the geometry of the right-angled triangle EOR in Fig. 143 the following relationships may be stated:

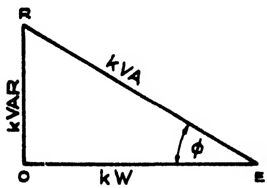


FIG. 143.—Graphical representation of power components in A.C. circuit.

Let $ER = a$, $OE = b$ and $OR = c$.
Then $a^2 = b^2 + c^2$
and $a = \sqrt{(b^2 + c^2)}$
or $kVA = \sqrt{(kW^2 + kVAR^2)}$

When any two of the quantities are known, the third can be calculated; the angle ϕ can also be ascertained from trigonometrical tables and the value of cos ϕ is equal to the power-factor.

If, in a single-phase circuit, three meters are installed, one to measure the kWh, a second to measure kVARh and a third to measure kVAh, these may be used to compare the results of observations under various loading conditions. Let it be assumed that a steady load of 100 amperes, 100 volts = 10 kVA, is maintained for one hour with a phase displacement of 15 deg. between voltage and current. At the end of this period, the advance on each meter register is noted. The angle of phase displacement is then increased to 30 deg., the load still being maintained at 100 amperes, 100 volts. At the end of another hour the advance on each register is again noted and this process is repeated for phase displacements of 45 deg. and 60 deg.

TABLE 9

Advances on the Registers of kVAh, kWh and kVARh Meters during Four Successive Periods at Different Power-Factors

a	b	c	d	e	f	g
kVAh	ϕ	cos ϕ	kWh	sin ϕ	kVARh	$\sqrt{(d^2+f^2)}$
10	15°	0·966	9·66	0·259	2·59	10
10	30°	0·866	8·66	0·500	5·00	10
10	45°	0·707	7·07	0·707	7·07	10
10	60°	0·500	5·00	0·866	8·66	10
—			—		—	—
40			30·39		23·32	38·3

The advances on the registers of the kVAh, the kWh and the kVARh meters during each successive period of one hour are shown in Table 9, columns *a*, *d* and *f* respectively. In column *g* is shown the calculated value of the kVAh derived from the root of the sum of the squares of the advances shown on the registers of the kWh and kVARh meters, which are in columns *d* and *f*, and in each case this calculated value agrees with the corresponding value in column *a*. If now we take the total registration on each meter over the period of four hours, during which the power-factor had four different values, we find that the calculated value of kVAh derived from the observed advances on the kWh and kVARh meters no longer agrees with the observed value of kVAh. Thus, the advance on the register of the kVA meter during the four hours is 40 kVAh; the corresponding advances on the kWh and kVARh meters over the same period are 30·39 kWh and 23·32 kVARh respectively. The calculated value of kVAh is as follows:

$$\begin{aligned} \text{kVAh} &= \sqrt{(30{\cdot}39^2 + 23{\cdot}32^2)} \\ &= \sqrt{(923{\cdot}55 + 543{\cdot}82)} \\ &= \sqrt{1467{\cdot}37} \\ &= 38{\cdot}3 \end{aligned}$$

The reason for this difference between the calculated and observed values of kVAh will be evident from Fig. 144. The small triangle *EWA* represents the circuit conditions during the first hour in which the advance on the kWh register is proportional to the base *EW*, the kVARh register to the side *WA*, and the kVAh register to the hypotenuse *EA*. The triangles *AXB*, *BYC*, and *CZR* represent the circuit conditions in the succeeding three hours. In each case the length of the hypotenuse is proportional to 10 kVAh and the arithmetic sum of these lengths is 40 kVAh. The advances on the register of the kWh meter are proportional to the sum of the base lines $EW + AX + BY + CZ$ or to the base line *EO*. Similarly the advances on the register of the kVARh meter are proportional to the sum of the sides $WA + XB + YC + ZR$ or to the side *OR*. The length of the hypotenuse *ER* is proportional to the calculated value of kVAh for the four hours, i.e. 38·3 kVAh and to the vector sum of the kVAh meter registrations. The length of the line *EABCR* is proportional to the arithmetic sum of the registrations during the same period.

From consideration of the foregoing example it will be evident that the numerical value of the kVA hours registered by a kVAh meter over

an extended period will be the same as the value arrived at by calculation from the observed advances on the registers of a kWh and a kVARh meter respectively, over the same period, provided that the power-factor does not vary; on the other hand, a variation in the power-factor will result in the value shown on the register of the kVAh meter being in excess of the calculated value. It will also be evident that with the power-factor varying from instant to instant, the equivalent of the line represented by *EABCR* in Fig. 144 will consist of a large number of infinitely short hypotenuses forming an irregular curve which will undulate if the power-factor varies up and down. The greater the variations in power-factor, the greater will be the discrepancy between the calculated and the observed values of the kVAh at the end of any time interval.

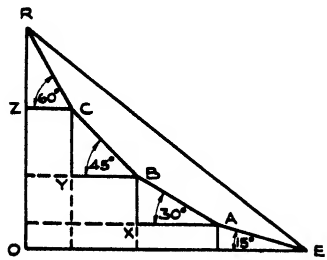


FIG. 144.—Difference between calculated and observed values of kVAh.

The objective when using a kVA meter is to measure maximum demand and not kVA hours. The time interval over which the actual demand is measured is comparatively short—15 to 30 minutes as a rule —and consequently wide variations in power-factor are unlikely to occur. Nevertheless, the demand indicator, which is in fact a registering mechanism starting from zero at the commencement of each time interval, will take into account the variations which occur and will give the arithmetic sum of these. In the single-phase case which has been considered for the sake of simplicity, the so-called arithmetic sum and vector sum instruments would indicate alike, irrespective of variations in power-factor. But the measurement of kVA maximum demand in single-phase supplies is of little practical importance, since these latter are confined mainly to domestic consumers who obtain their currents as a rule under tariffs in which maximum demand measurements are not made. In three-phase supplies, three single-phase instruments could be used, each measuring the maximum demand in one of the lines, but this procedure is objectionable. In the first place, the cost of three separate instruments would be considerably greater than the cost of a combined three-phase demand indicator and secondly, the maximum demand on each phase may occur at different times or on different days. Should this be the case the sum of the three separate

maximum demands would be in excess of the actual simultaneous maximum.

In a three-phase circuit in which the load is balanced equally on the three phases and the power-factor is the same on each, all the demand indicators which have been described will, theoretically, read alike, subject of course to the power-factor being within certain limits in the case of the restricted range pattern. Differences in the indications will occur, however, if the load is unbalanced or if the power factor differs in the different phases. Consider the case of a three-phase load in which the line currents are balanced and lag 30 deg., 45 deg. and 60 deg. respectively, as shown in the vector diagram in Fig. 145 by the vectors I_R I_Y I_B. The components of these currents are shown in Fig. 146, where the base lines *EW*, *AX* and *BY* represent the respective energy components and the sides *WA*, *XB* and *YR* the reactive components. The three hypotenuses *EA*, *AB* and *BR* which are of equal length represent the line currents I_R, I_Y and I_B lagging 30 deg., 45 deg. and 60 deg. respectively behind the phase to neutral voltages E_R, E_Y and E_B in Fig. 145.

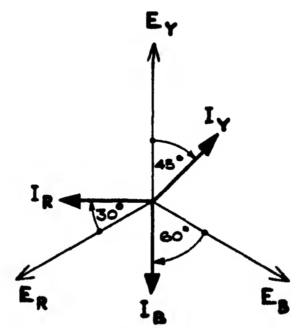


FIG. 145.—Vector diagram for three-phase load, balanced currents, all lagging.

An energy meter connected in the three-phase supply will register at a rate proportional to the sum of the three base lines, or to the line *OE*. A reactive meter will register at a rate proportional to the sum of the three vertical sides or to the line *OR*. A kVA meter of the vector-sum pattern will register at a rate proportional to the hypotenuse *ER* which latter is the vector sum of the hypotenuses *EA* and *AB* and *BR*. A kVA meter of the arithmetic sum pattern will register at a rate proportional to the arithmetic sum of $EA + AB + BR$ which is the line *EABR* and as this line is obviously greater in length than the hypotenuse *ER*, the registration will be correspondingly greater than that of the vector-sum meter.

Now consider the case of a three-phase load in which the line currents and the phase displacement between currents and voltages have the same values as in the previous example, but the current I_B in the blue line is leading by 60 deg. instead of lagging by the same angle. This condition is shown in Fig. 147 which may be compared with

Fig. 145. The components of the currents are shown in Fig. 148, which may be compared with Fig. 146, and both are drawn to the same scale. The energy meter will register at a rate proportional to the sum of the

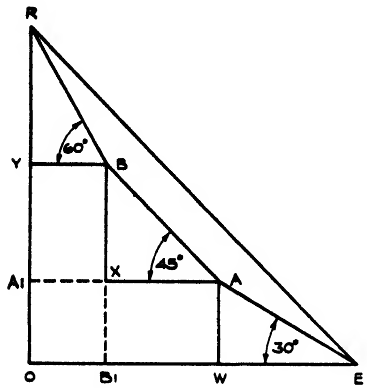


FIG. 146.—Diagram showing difference between arithmetic and vector sum of kVA in three-phase circuit. Balanced currents at different power-factors.

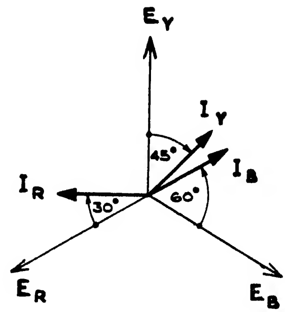


FIG. 147.—Vector diagram for three-phase load, balanced currents, blue phase leading.

base lines $EW + AX + BY = OE$ as before. The reactive meter will register at a rate proportional to the sum of the vertical sides, but as the current I_B in Fig. 147 is leading, the reactive component now includes

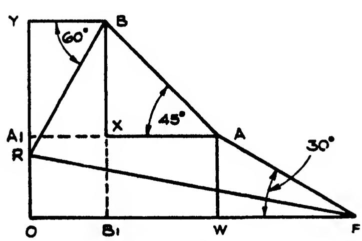


FIG. 148.—Diagram showing difference between arithmetic and vector sum of kVA in three-phase circuit with balanced currents, blue phase leading.

a negative quantity; the reactive registration will therefore be proportional to $WA + XB - YR = OR$. A kVA meter which measures the vector sum of the advances on the kWh and kVARh meters will register at a rate proportional to the hypotenuse ER, but a meter

measuring the arithmetic sum will register at a rate proportional to the length of the line *EABR*.

It may be noted that the disparity between the registrations on the two types of kVA meter is much greater in the second example than in the first. Also the meter registering the arithmetic sum shows the same advance in both examples, as it is independent of variations in power-factor. A further point to note is that, in both examples, it has been assumed that the power-factor during the maximum demand time interval did not vary, although the power-factor of each phase was different. If the power-factor during the same time interval had varied then the hypotenuse of each triangle would be replaced by a curve or a wavy line as was indicated in considering the single-phase case represented by Fig. 145.

Brief reference may be made to the effect of unbalanced loads, an extreme case of which would be a single-phase load connected between two of the lines. A single-phase non-inductive load would cause no registration on a three-phase reactive meter and consequently a kVA meter which combined an energy and a reactive measuring element would show an advance identical with the advance on a kWh meter. A three-phase load in which lagging current in one phase and leading current in another are combined in such proportions as to constitute the equivalent of a load having a power-factor of unity would also cause no registration on a three-phase reactive meter and a kVA meter of the vector sum pattern would indicate the same amount as a kWh meter on the same load. In both these examples a kVA meter of the arithmetic sum pattern will indicate an amount considerably in excess of that shown on the vector sum instrument and it would be correct to state that in all cases where a disparity exists between the indications of the two patterns of meter, the instrument measuring the arithmetic sum will indicate the greater quantity.

A final example may be cited to illustrate the amount of divergence which can occur in extreme cases between arithmetic sum and vector sum instruments. Assume a load on a three-phase four-wire system, consisting of 10 amperes per phase, in which the load on the red phase is due entirely to capacitive current leading the voltage by 90 deg., the load on the yellow phase being non-inductive and in phase with the voltage, and the load on the blue phase entirely inductive, lagging behind the voltage by 90 deg. The currents in the red and blue phases are equal and contain no energy component. As one leads by 90 deg. and the other lags by the same amount, a reactive meter in the circuit

will tend to rotate in the backward direction due to the leading current and in the forward direction due to the lagging current; these two opposing forces cancel out and produce no registration. There is no reactive component in the yellow phase and consequently no registration whatever on the reactive meter. An energy meter in the same circuit will be actuated only by the non-reactive load in the yellow phase since there is no energy component in the red and blue phases.

A kVA meter which combines kWh and kVARh elements will indicate a maximum demand in accordance with the expression:

$$\text{kVA} = \sqrt{[(\text{kW})^2 + (\text{kVAR})^2]}$$

and since in this case the registration on the reactive meter is zero the kVA demand will equal the kW demand. But a kVA meter which gives the arithmetic sum of the loads on the three phases and which is independent of power-factor, will in this case indicate a demand three times as great as the vector sum instrument, since the loads on the red and blue phases will be additive instead of cancelling out. The worst discrepancy which could arise would be where the non-reactive load in the yellow phase is switched off, in which case the arithmetic sum instrument would indicate two-thirds of the previous amount and the vector-sum instrument would indicate zero.

The conditions in this example, which is purely hypothetical, are quite unlikely to arise in practice and the example has been introduced in order to explain differences of lesser magnitude which may occur from time to time. Fortunately for the peace of mind of meter engineers the nature of industrial power loads is such that wide variations in power-factor and in the distribution of the load on the different phases do not occur with great frequency, or alternatively, when they do occur only one type of instrument is involved in the measurement of maximum demand and the consumer is unaware of any possible discrepancy.

The advocates of the arithmetic sum definition of three-phase kVA maintain that, for the basis of a tariff, it has advantages over the vector sum definition. It is claimed, and with some justification, that if the load on a feeder or distributor is unbalanced, the feeder cannot be used in the most effective manner because the maximum loading occurs when any one conductor is carrying its maximum rated current, even though the other conductors are carrying a much smaller current. The same objection applies also to the loading of the plant in the sub-station and generating station. But if the load on the generating station, sub-station, feeder or distributor is shared between a number of consumers

the diversity of the loads and the variation in the times of their maximum demands tend to level out the inequalities and render the latter of less importance from the point of view of the supply authority. In the case of a large consumer, the diversity of load on his own premises will tend to produce a fairly well-balanced total load, even though individual portions are badly out of balance.

Having dealt at length with some of the ambiguities which arise in the measurement of kVA maximum demand, the position may be summarized as follows: there is no legal definition of kVA or power-factor in a three-phase circuit and more than one definition is possible under certain conditions. Two main types of instrument are available for measuring kVA maximum demand, one conforming to the vector-sum definition and the other to the arithmetic sum. When the currents between line and neutral are balanced and the power-factor is the same in each phase (all currents lagging or all currents leading), both types of instrument will indicate the same value of kVA; if the currents are unbalanced or if the power-factors differ the indications of the two types may differ. Similarly, if the currents are equal in value but the current lags in one phase and leads in another, the indications of the two types will differ. Wherever there is a difference, the arithmetic sum indication will be the greater of the two. In extreme cases the differences may be very substantial, but in practice these extremes are seldom encountered.

Instruments which measure the vector sum quantity may be subdivided into two types, one of which is suitable for a very wide range of power-factor and the other is suitable for a restricted range only. Provided that the power-factor at the time of maximum demand falls within the range for which the meter is constructed close agreement may be expected between the indications of the restricted-range and wide-range types. If a restricted-range meter is used and the power-factor at the time of maximum demand is outside the restricted range, the indication will be less than the value shown on a wide-range meter. The author ventures to express the opinion that, in all but exceptional cases, the restricted range instrument fulfils all practical requirements, provided that a wise choice of range is made. Certainly this is the case where comparatively small installations are concerned, both from the point of view of simplicity and of moderate first cost. It will be found in the majority of cases that the selection of a wide-range instrument confers no advantage because the maximum demand occurs at a power-factor well within the range covered by a restricted range instrument.

CHAPTER X

MAXIMUM-DEMAND INDICATORS

10.1. The Maximum Demand System. The maximum demand system of charging for supplies of electricity was introduced towards the end of the last century as a means of arriving at an equitable price for the services rendered. It was recognized that the cost of supplying electricity could not be covered by charging a flat rate per unit or kWh, and that a number of factors must be taken into consideration if the prices which different consumers were called upon to pay were to be equitable as between one consumer and another.

The cost of supplying electricity may be divided roughly into two parts, referred to as fixed charges and running charges respectively. Unlike gas and water, for example, electricity cannot be stored economically and sufficient plant such as boilers, generators, transformers, transmission and distribution systems must be provided and maintained in order to satisfy at any and every moment the immediate requirements of each consumer. The demand for electricity is to a certain extent seasonal, and the amount of plant provided must be sufficient to deal with the maximum load whenever it occurs. The installation of this plant involves substantial capital expenditure in the first instance and provision must also be made for its replacement when necessary. The interest on the invested capital and the cost of plant maintenance and renewal constitute important parts of the fixed charge and each consumer should bear his own proportion of this cost. The running charge is made up principally of coal costs which vary substantially in proportion to the amount of energy supplied.

Unlike the running charge, the fixed charge may bear little relation to the total consumption, and can vary considerably as between different consumers. Take for example two hypothetical consumers *A* and *B*, each of whom requires 1,000 kWh per working day of ten hours. In the case of *A*, a steady load of 100 kW is maintained throughout the day, the consumption being at the rate of 100 kWh per hour. In the case of *B*, the load fluctuates between a low value and a maximum of 400 kW, although the total consumption at the end of the day is in fact the same as for A. The same amount of coal will be consumed in the generating station for each, but the amount of generating plant

necessary for meeting the requirements of *B* will be four times as great as for *A*. It is obvious therefore that the fixed charges involved in supplying current to *B* are much greater than in supplying to *A*, and in fairness, the price charged to the latter for the service rendered should be correspondingly smaller.

The ratio of the fixed charge to the running charge varies considerably and would be at a minimum for a consumer who maintained a steady uninterrupted load throughout twenty-four hours per day. It is not at all uncommon in the case of certain classes of consumer for the fixed costs to be equal to if not greater than the running costs, and it was to enable the supply authority to discriminate fairly between different classes of consumer that the maximum demand system of charging was first introduced. In all cases where such a charge is made, the maximum demand, as measured, is not based upon an instantaneous value of the load as shown by an ammeter or wattmeter, but upon an average value or something akin thereto, measured over an interval of time, which in practice is usually between fifteen and sixty minutes.

10.2. Maximum Demand Tariff as Applied to Domestic Consumers. In the early days of electricity supply, domestic consumers were in the majority and the load consisted mainly of current for lighting purposes. The individual loads were comparatively small and the revenue derived therefrom did not justify the expenditure of a large sum per consumer for the provision of a maximum demand indicator in addition to an electricity meter. The Wright Maximum Demand Indicator made by the Reason Manufacturing Co. Ltd., was one of the first to be introduced, and being of simple construction and moderate in first cost was used extensively in domestic installations. As a description of this indicator follows later, it will suffice for the moment to say that this is a thermal instrument giving an indication of the maximum sustained current carried by the installation during any period of thirty minutes or more.

A consumer receiving a supply under a maximum demand tariff had installed in his premises in addition to the usual kWh meter, a maximum demand indicator. His quarterly account for current included two items the one being the charge for the current consumed in kWh, and the other a charge proportional to the maximum demand in amperes. These items correspond to the running and fixed charges respectively. It was usual under this tariff to charge a lower price per kWh than that charged to a consumer under a flat rate tariff. If the load consisted

entirely or mainly of lighting, the number of lamps in use and consequently the maximum demand probably would not vary substantially with the season of the year. In such a case the maximum demand charge would show little variation between one quarter and another, but the hours of lighting during the winter would be longer than in the summer, with a correspondingly greater charge for current consumed. Thus, taking the maximum demand charge into consideration, the average price per kWh during the summer quarter would be higher than during the winter. The maximum demand indicator was reset to zero at the end of each quarter when the meter reading was taken.

A variation in this tariff which achieved the same result and which perhaps caused less perplexity to the consumer was to charge a higher price for a certain number of kWh per quarter, based on the maximum demand, all remaining consumption being charged for at a lower price. For this purpose the maximum demand indicator was provided with two scales, one reading in amperes and the other a corresponding number of units to be charged at the high price. The difference between the high and low prices per unit multiplied by the number of high-price units would correspond to the value of the maximum demand charge under the other method of charging.

Although efforts were made by many supply authorities to foster the maximum demand tariff, it was never properly understood by the ordinary domestic consumer and never became popular. An occasional heavy load, due for example to a Christmas celebration, could penalize the consumer for the whole of a quarter, and disputed accounts were not unusual as a result. The maximum demand tariff as such is now seldom applied to domestic consumers in this country and other tariffs such as a two-part tariff have taken its place. It is usually agreed however, that the maximum demand system is basically sound, and the object of the majority of alternative tariffs is to achieve the same results without resort to actual measurement of the demand.

10.3. Maximum Demand Tariff as Applied to Industrial Consumers. The object of a maximum demand tariff is not so much to penalize a consumer for having an excessive load as to encourage him to avoid sustained high peaks, and to maintain so far as is possible a steady load for long periods. The knowledge which will enable this desirable condition to be achieved is frequently absent in the case of the ordinary domestic consumer, but is more often appreciated by the industrial consumer, and many supply authorities give the latter the option of taking a supply under a maximum demand tariff on advantageous terms.

The usual form of tariff as applied to large power users is to make a fixed charge of a certain amount per kW of maximum demand per month or per annum, plus a further sum per kWh consumed. The magnitude of the maximum demand is determined month by month as a general rule, but in some cases it may be ascertained quarterly or annually. The actual charges under this tariff are of the order of £6 to £12 per annum per kW of maximum demand, plus (for example) $\frac{3}{4}$d per kWh for all units consumed. These charges may vary up or down according to the nature of the load and with the particular supply undertaking concerned. Many undertakings measure the maximum demand in kVA instead of kW.

There are many variations in the foregoing simple form of tariff intended to encourage the use of electricity and at the same time to benefit the supply undertaking. One such variant is what is known as a restricted-hour demand tariff, according to which, the measurement of the maximum demand is confined to those periods during which the supply undertaking is carrying its peak load. For example, on Sundays in industrial areas where the majority of manufacturing premises are not working, the load on the generating plant is comparatively small, and additional load at such a time is welcome to the supply undertaking. Similarly on weekdays between 8.0 p.m. and 6.0 a.m., light-load conditions prevail, and no useful purpose is served by restricting load at such a time. To encourage the use of electricity during these periods of light load, the maximum demand indicator is put out of action. Alternatively two instruments are installed, one to measure the maximum demand during "peak-load" hours and the other to measure during "off-peak" hours; a lower charge per kW is made for the "off-peak" demand.

10.4. Types of Maximum Demand Indicator. Since the introduction of the maximum demand tariff in 1892, many instruments have been constructed for the purpose of indicating the magnitude of the maximum demand. These include thermal, electromagnetic and integrating instruments, of which the thermal and integrating types are the most important. All share one feature in common, namely, that the quantity measured is not an instantaneous value but an average, or an approach thereto, over some predetermined time interval. In current practice this time interval is referred to as the demand interval or demand integration period. While the term "demand interval" may be used with respect to all types of demand indicators, the term "demand-integration period" is preferable in the case of integrating instruments and will be

used when referring to these latter specifically. A demand interval of thirty minutes is commonly adopted in this country for the majority of industrial loads and bulk supplies but a fifteen-minute demand interval is common in some other countries.

Thermal maximum demand indicators may be divided into two main classes, both of which depend upon the heating effect of the current in the main circuit for producing an indication. In one class, a glass U-tube containing a liquid has two bulbs containing air, attached to its extremities. One of the bulbs is surrounded by a heating element which, when carrying current, causes the air inside the bulb to expand and depress the level of the liquid in the limb of the U-tube to which it is attached. The level of the liquid in the other limb rises and overflows into a reading tube from which it cannot return. The height of the liquid in the reading tube is a measure of the maximum demand in amperes over an interval of time.

The other class of thermal instrument usually consists of two bimetallic elements in the form of spiral springs. A heating element which carries the current in the main circuit is mounted in such a manner that it can influence one spring only, the other spring being shielded from its influence. When current passes through the heating element, the adjacent bimetallic spring tends to become deformed. The resulting movement of the spring is communicated to a pointer which moves across a scale and indicates the magnitude of the demand. A second pointer, frictionally retained in position, is pushed forward by the first. When the current is reduced in value the first pointer returns towards zero, but the second remains in the position to which it has been pushed and serves to indicate the maximum current which has passed through the instrument.

In addition to the foregoing there is a further class of thermal maximum demand indicator which incorporates a heating element actuated by the current and the voltage of the supply. This instrument has been used extensively in Canada and the United States of America, but has not found much favour in this country. Normally the scale and pointer show the maximum demand in kW, but by a modification the instrument can be arranged to indicate in kVA over a restricted range of power-factor. Two bimetallic springs are provided which act in opposition. Two heating elements are arranged in a circuit in such a manner that with no load in the main circuit the temperatures of both elements are equal. Under load conditions the temperature of one element is increased and the other reduced. This differential action

causes one of the springs to exert a greater torque than the other and to move a pointer across a scale. A non-return pointer pushed forward by the former indicates the maximum demand.

Maximum demand indicators of the integrating type usually consist of an integrating meter, direct current or alternating current as the case may be, together with a mechanism driven by the meter and controlled by a time-switch or some other form of time element. The system of measurement which is adopted almost universally for tariff purposes where industrial loads are concerned is that originally introduced by Merz. It consists in dividing the demand assessment period into a large number of equal intervals of time, measuring by integration the average demand in each successive interval and selecting the particular interval during which the maximum average demand occurred, to give an indication on a scale of the magnitude of the demand experienced.

The method of operation of a Merz maximum demand indicator is briefly as follows:—A train of wheels is driven from one end by an integrating meter, and terminates at the other end in a non-return pointer which can be pushed around a scale in the forward direction. At some point in the train the gears can be momentarily disconnected to allow the mechanism driving the pointer to return to a zero position. The momentary disconnection of the gears takes place at regular intervals and the time between any two successive disconnections is referred to as the integration period. The integration period (usually thirty minutes) is determined by a time-switch which effects disconnection of the gears through a mechanical coupling or by electromagnetic means.

Where electromagnetic means are employed to disconnect the gears it is desirable that the mechanism shall normally be disengaged and shall be held in engagement electrically; this is necessary in order to avoid the possibility of an excessive demand being registered owing to an interruption in the supply. If a temporary interruption should occur shortly before the end of an integration period and a restoration shortly afterwards, a demand mechanism which was normally in gear would not receive the resetting impulse when it became due. The result would be that an integration period approaching possibly twice the normal duration would occur, with the possibility of an excessive demand registration. For this reason demand mechanisms which are electrically "held in" are employed when time-switch control is used. This necessity does not arise if an electrically-driven timing element is used since this element will stop when there is a failure in the supply.

At the commencement of each demand assessment period, that is, the period between successive meter readings by the supply authority, the pointer and the mechanism are reset to zero. During the first integration period following reset, the pointer is pushed up the scale by the meter driving through the train of wheels. At the end of the integration period the time-switch disconnects the gears and a spring restores the mechanism to a zero position leaving the pointer in the position reached at the moment of disconnection. If in subsequent integration periods no increase in the average value of the load occurs, the pointer will remain undisturbed, but if the average load is increased the pointer will be pushed higher up the scale. The distance moved by the driving mechanism is a measure of the average load during an integration period and the position of the pointer at any time is a measure of the maximum average load which has been experienced in some one of a succession of integration periods since the pointer was last reset to zero.

The demand indicator mechanism is sometimes combined with the kWh register in a single unit as this permits a more compact arrangement of the gearing; in some cases a timing element is also incorporated in the combination. These combinations are not without their disadvantages however; should it be necessary to carry out adjustments or repairs on site, these are usually facilitated if the elements are separate units. The kWh register is unlikely to require maintenance work and where this remains a separate unit as in an ordinary kWh meter, it can remain undisturbed while the demand indicator mechanism and/or the timing element is removed entirely for overhaul or repair. The temporary withdrawal of a demand indicator mechanism from service may not be of serious importance, but the removal of the kWh register entails a loss of registration which it is most important to avoid.

10.5. Characteristics of Maximum Demand Indicators. If a number of maximum demand indicators are connected in series with a load it would be reasonable to expect that all should read like; this expectation will be realized only provided that certain conditions are fulfilled. If the load is variable and with peaks of short duration the possibility of discrepancies being observable in some types is considerable. Since the maximum demand charge may represent a substantial proportion of the total cost of a supply of electricity, it is desirable that some consideration be given to the factors which may contribute to these discrepancies. The only demand indicators of practical importance to-day are the thermal and the integrating (Merz) types, and the characteristics of these will be considered separately.

Demand indicators of the thermal types used in this country are actuated by current values only. The scale may be arranged to read in amperes, or alternatively in kW or kVA at the declared voltage of the supply on which they are operating. Since the heat produced in the current element varies as the square of the current, the indication on the instrument may be expected to vary in a similar manner. The sub-divisions of the scale are crowded together at the lower end and widen out considerably at the upper end; in some instruments an indication of one-fifth of full scale reading may be located at one-twentieth to

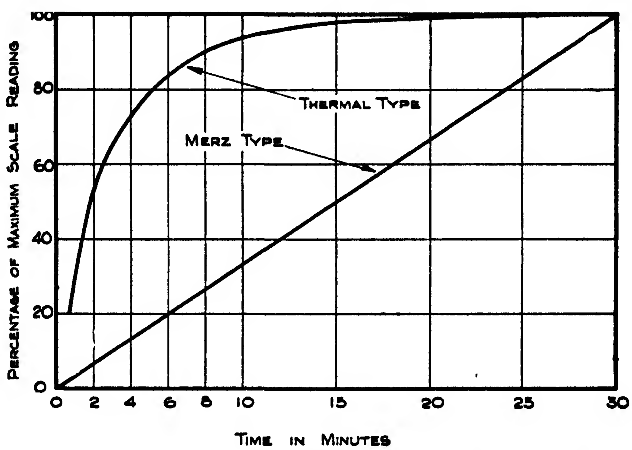


FIG. 149.—Comparison between rates of increase in reading on thermal and Merz pattern demand indicators.

one-twenty-fifth of the scale length from zero. Indications below one-fifth or one-sixth of the full-scale are usually omitted.

The time lag or demand interval of a thermal demand indicator, that is, the time which elapses after the application of a steady load until the maximum indication is reached at that load, can be selected from a wide range of possible alternatives. Instruments can be obtained having a demand interval as short as five minutes to as long as three hours, according to the purpose for which they are intended. For the purpose of electricity tariffs, a thirty-minute demand interval is usually adopted. The rate of increase in the indication of a thermal demand indicator, from the time of switching on the load until the maximum indication is reached at that load, varies considerably as between instruments by different makers and also between different ratings by the

same maker. In general, the shape of the curve showing the rate of increase in indication is logarithmic, but considerable departure from a true logarithmic curve may be observed; one such curve representing the application of a steady load to a thermal demand indicator having a demand interval of thirty minutes is shown in Fig. 149. Another curve on a different type of thermal instrument is shown in Fig. 150, the conditions of test being similar in both cases. It may be noted that although the final indication at the end of thirty minutes is the same in both cases, the initial rate of increase is considerably greater in Fig. 150 than in Fig. 149. It is possible for the manufacturer to alter the shape of the curve by the use of heat storage devices or by baffles between the heating element and the indicator element.

The scale of a demand indicator of the Merz pattern is uniformly divided from zero to the maximum indication, consequently an instrument of this type can be used to provide accurate readings down to much lower values than is possible with a thermal instrument. The rate of increase in the indication with a steady load follows a straight line law as shown on the curve in Fig. 149. With a variable load the rate of increase in the indication will be at all times proportional to the load. At the end of each integration period, the advance registered by the driving mechanism and the driving pointer, if any, will be strictly proportional to the average load during the interval.

The characteristics of Merz demand indicators for the measurement of kW maximum demand are all alike, and instruments made by different manufacturers, if connected to the same load, will give the same indications, assuming of course that the calibration is correct in each case and that the operating conditions are the same. This statement is correct irrespective of whether the load is steady or variable: it is necessary however, to observe that where two or more demand indicators are measuring the same load, all are reset at the same time, preferably by means of one time-switch. Alternatively, if each instrument has its own time-switch, or if self-contained timing devices are provided, the integrating periods should be synchronized. This procedure is necessary in order to ensure that the operating conditions are identical for each instrument.

10.6. Performance of Thermal and Merz Demand Indicators Compared. It has been stated in an earlier paragraph that if a number of maximum demand indicators of differing types are connected in series, and a load is applied for a sufficiently long period, all the instruments should give identical indications. This presumption is correct only under certain

conditions, and in practice these conditions may not be fulfilled. It is now proposed to give consideration to some of the factors which may result in discrepancies in the indications of these instruments.

A fundamental difference between thermal and integrating types of demand indicator is that, in general, thermal types are actuated by current values only, and integrating types by power values. For tariff purposes it is required to know the demand in kW or kVA and this necessitates the calibration of thermal instruments at the declared voltage of the supply on which they are to operate. If, at the time the maximum demand occurs, the supply voltage is low, then the value indicated will be too high. This is a not unlikely contingency since, at the time of maximum load, the voltage drop in long feeders and distributors may be sufficient to influence adversely the terminal voltage of those consumers situated near the end of such distributors. A five per cent. reduction in supply voltage at the time of maximum demand would result in the consumer being overcharged by a like amount.

Another fundamental difference between thermal and integrating types of demand indicator is in the shape of the curves relating the rate of increase in the reading of the demand indicator with time. This is shown clearly in Fig. 149 where two curves, one for a thermal instrument and the other for an integrating instrument, may be compared. The curves relate to a steady load applied for a period of thirty minutes to instruments which have been set to zero before commencing the test. It will be noted that the reading on the integrating instrument advances at a uniform rate and all types of integrating instrument behave in a similar manner. The advance on the thermal instrument is very rapid at first and very slow towards the end of the period. Thermal types do not all behave alike and although the curve relates to one particular instrument there are some which advance more rapidly and others more slowly. The curve which is approximately square-law for all thermal instruments eventually becomes horizontal, but as the approach is gradual it is difficult to state with exactitude when finality has been reached, and consequently it is difficult to state the demand interval with precision.

Consideration of the characteristics shown in Fig. 149 will indicate that if the load is of a variable character considerable differences will occur between the readings shown on different types of instrument. For example, suppose that the load during the first ten minutes of a demand interval is equal to the maximum load for which the demand indicator is scaled. During this time the integrating instrument will

register a demand equal to thirty-three and one third per cent. of the maximum scale reading, but the thermal instrument will have registered a demand equal to approximately ninety-four per cent. of the maximum scale reading. If now the load is switched off for the remainder of the demand interval, these indications will remain as a record of a maximum load which has been reached. Such an extreme condition is not likely to arise in practice, but the example does indicate that with a variable load such as occurs frequently in practice, the thermal instrument will give an indication much higher than the integrating instrument, particularly if there should be one peak of short duration during the demand assessment period. On the other hand, a condition may arise under which the integrating instrument could under-register the maximum demand. If the maximum load during an assessment period be of thirty minutes duration or less and if this load be spread equally over two integration periods, then the instrument would register a demand less than the true maximum.

To summarize the foregoing comparisons it may be stated that there is a tendency for the true maximum demand to be over-registered on a thermal instrument and under-registered on an integrating instrument. It is usually regarded as desirable by a supply authority that where there may be a doubt as to the accuracy of a measurement, the benefit of the doubt should be given to the consumer. For this reason, therefore, apart from others, demand indicators of the integrating type are usually adopted for measuring the maximum demand of large power consumers who receive a supply under a maximum-demand tariff.

10.7. Examples of Maximum-Demand Indicators. Thermal maximum-demand indicators were developed originally for use on comparatively small installations and as such were single-element instruments suitable for connection to direct or alternating-current two-wire services. The use of three instruments on the three-phase three- or four-wire circuits was attended with certain disadvantages and the manufacturers of these demand indicators introduced modifications with the object of rendering them more suitable for this service. Maximum-demand indicators of the integrating type are usually associated with a polyphase meter as their use in this country is confined almost entirely to power consumers' circuits or to the metering of bulk supplies. In Canada and the United States of America demand indicators of the thermal and the integrating types have been developed for use on small installations. The integrating type has been constructed as an attachment to the register of a single-phase meter and, together with a self-contained

timing element, has been included in a meter case of more or less normal dimensions. Brief descriptions of some well-known maximum-demand indicators used in this country follow.

10.8. Wright Maximum-Demand Indicator. The Wright maximum-demand indicator manufactured by the Reason Manufacturing Co. Ltd. is a thermal instrument, and although introduced about fifty years ago, its constructional features have changed very little since that time. Two views of the instrument with the case closed and open respectively are shown in Fig. 151. The instrument may be described as a differential recording thermometer which measures the heat pro-

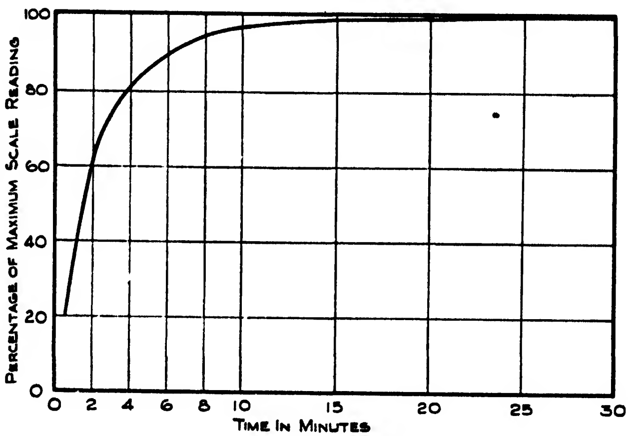


FIG. 150.—Rate of increase in reading on another type of thermal demand indicator.

duced by an electric current. It consists of a glass vessel having two bulbs of approximately the same size, connected by a U-shaped tube containing sulphuric acid, and is provided with a third or "reading tube" connected to the upper end of the right-hand limb. A strip of resistance metal is wrapped round the left-hand bulb and through this the current to be measured passes, raising the temperature of the strip according to the intensity of the current. The effect of this is to expand the air in the left-hand bulb, depressing the column of liquid below it. The liquid rises in the other limb and slowly overflows into the reading-tube, the final height to which it rises in this tube indicating the maximum steady current which has passed through the instrument. A scale adjacent to the reading tube permits the value of the maximum current

in amperes to be observed. A second scale graduated in equivalent values of kW or kVA at the declared voltage of the supply can be provided if desired.

The time lag or degree of sluggishness of registration of the maximum demand can be varied between thirty minutes and three hours. A

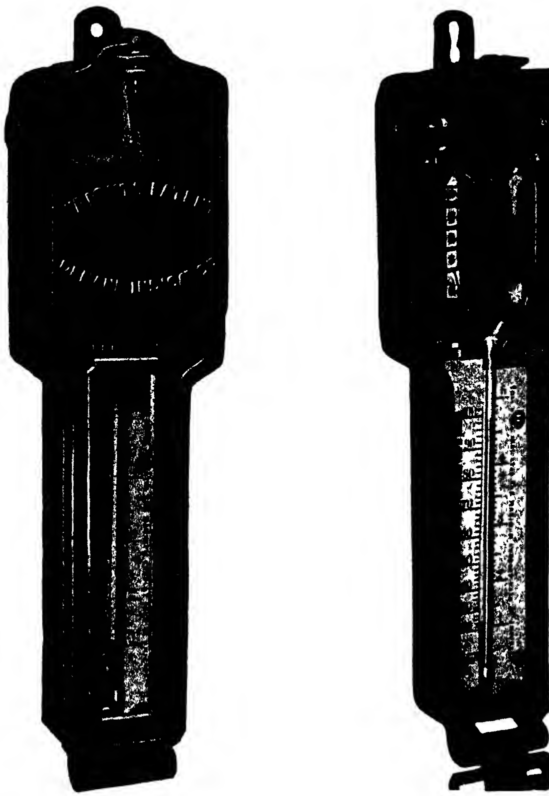


FIG. 151.—Wright thermal maximum-demand indicator.

curve showing the rate of increase in the indication of the Standard Type instrument, that is, the one with the shortest time lag or demand interval, appears in Fig. 150. This curve which rises rapidly at the commencement shows that at two minutes from the application of a steady load an indication equal to sixty per cent. of the maximum indication for that particular load has been reached, and at six minutes,

the indication has risen to ninety per cent. At thirty minutes the curve has become horizontal and the maximum demand indication may then be observed. A more sluggish instrument referred to as the Absorber Type, and one more sluggish still, referred to as the Cylinder Type, have been designed specially for power users. The time-lag is produced in the Absorber Type by the introduction of a piece of iron or glass into a pocket in the heating bulb, and in the Cylinder Type by an insulated cylinder of cast iron placed between the coil and the bulb.

The scale of the instrument is calibrated from the maximum reading down to one-fifth of the same and over this range is approximately 4½ inches long. The indications are guaranteed by the manufacturer to be within plus or minus 2½ per cent. of the maximum scale reading at any part of the scale. Equality in the size of the two bulbs ensures absence of temperature error, as any variation in atmospheric temperature will affect the air in both bulbs to the same extent. To avoid transfer of air from one bulb to another during transport, a series of traps are inserted in the U-tube. If however, owing to rough handling, there should be any transfer of air, or if air bubbles are trapped in the U-tube, errors in indication will result. This condition can be rectified by following instructions issued by the manufacturer.

The glass vessel is mounted on a board, hinged at the top and secured by a spring clip at the bottom, the whole being contained in a cast-iron box. At the end of each assessment period, quarterly or annually as the case may be, the indicator is set to zero by opening the box and raising the glass vessel so that the reading tube is elevated above the bulbs. This allows the liquid to drain out of the reading tube, after which the vessel is restored to its normal position. Flexible copper connections between the resistance strip and the terminals are provided to facilitate this movement.

For measuring the maximum demand in a three-phase circuit, it is not desirable to use three indicators connected one in each phase. Such an arrangement does not take into account the possibility that the maximum load on each phase may not occur at the same time and consequently the sum of the three readings would then give a value in excess of the true simultaneous maximum demand. To overcome this defect the Reason Manufacturing Co. have developed a three-phase maximum-demand indicator which can be used in a three-wire or four-wire system, and which they claim is accurate within plus or minus 2½ per cent. when the loads on the three phases are approximately balanced.

The actual demand indicator is the standard single-element instrument, fitted with an appropriate scale to indicate the three-phase load, and combined with a rectifier unit comprising three small current transformers and three rectifiers. Each of the three-phase lines passes through the primary of a current transformer, and each secondary is connected to a rectifier. All three rectifiers are connected in parallel on the output side to the heating element of the demand indicator. The method of carrying out these connections is shown in Fig. 152. The rectified current supplied to the heating element is the sum of the currents from the three rectifiers and is directly proportional to the arithmetical sum of the currents in the three phases at any instant. The instrument is subject to error on unbalanced loads or loads in which the power-factor is not the same on each phase. In an extreme case where

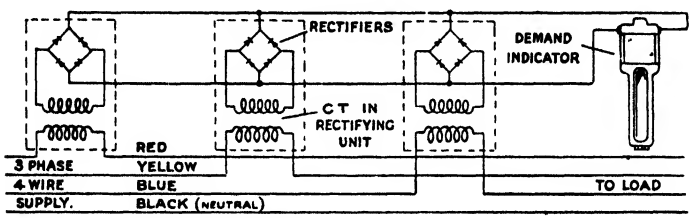


FIG. 152.—Wright three-phase maximum-demand indicator.

one phase only is loaded, the error will be approximately 10 per cent. plus. It is unlikely however, that the maximum load could occur when one phase only is loaded and as a state of balanced load is approached, this error becomes progressively less.

10.9. "P and B" Maximum-Demand Indicator. The "P and B" maximum-demand indicator is a thermal instrument manufactured by the "P and B" Engineering Co. Ltd. It is produced in several patterns and the two most useful for consumers' installations are the Type HSB in a bakelite case or the Type HSI in a cast-metal case. Both types are supplied as whole-current instruments in a range of ratings between 2·5 and 100 amperes inclusive. An illustration of the Consumers' Type HSI appears in Fig 153 and a view of the movement removed from the case is shown in Fig. 154. The indicator is actuated by current values only and is scaled to read in amperes of maximum demand. For tariff purposes an alternative scale reading in kW or kVA at the declared voltage of the supply can be provided if desired.

The movement shown in Fig. 154 consists of two bimetal coils (*a*) and (*b*) with an insulated heater (*c*). The two coils are supported by their centres on a horizontal stainless steel spindle. The actuating coil (*a*) is fixed by its centre to the spindle and the other or compensating coil (*b*) has an indicating pointer (*d*) attached to its centre which forms a

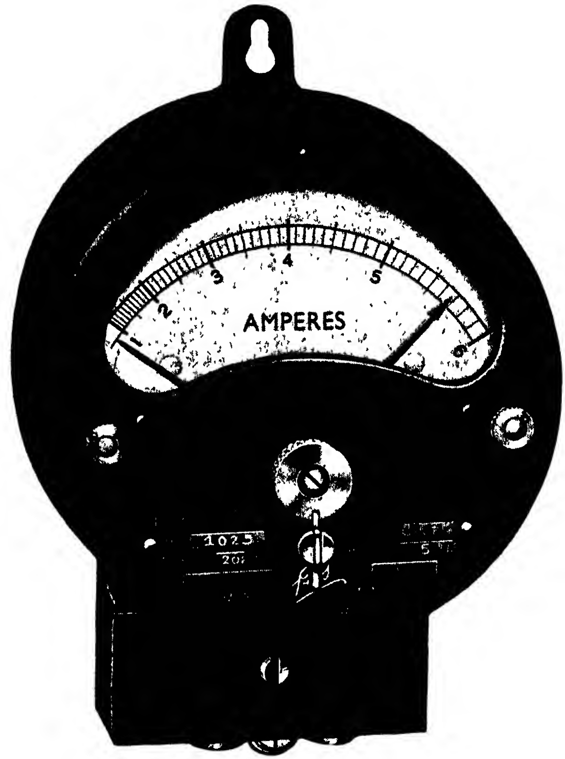


FIG. 153.—'P & B' thermal maximum-demand indicator. Type HSI.

sleeve bearing, the outer ends of the coils being joined together by the yoke (*e*). The coil (*a*) is actuated by heat communicated from the heating element and is separated by a baffle (*f*) from the compensating coil.

When current passes through the heating element, the heat developed causes the coil to close up. The resulting movement of the outer end of the coil is transmitted through the yoke and top coil to the pointer

attached to its centre. This causes the pointer to travel across the scale, carrying forward with it a second or maximum pointer which remains at the maximum reading, where it is held by a light frictional device until reset by hand. Any change in the ambient temperature rotates the free outer ends of the two coils through the same angle without causing any movement of the pointer, thus rendering the instrument free from any inherent temperature errors.

The time-lag of the instrument is determined by the dimensions of

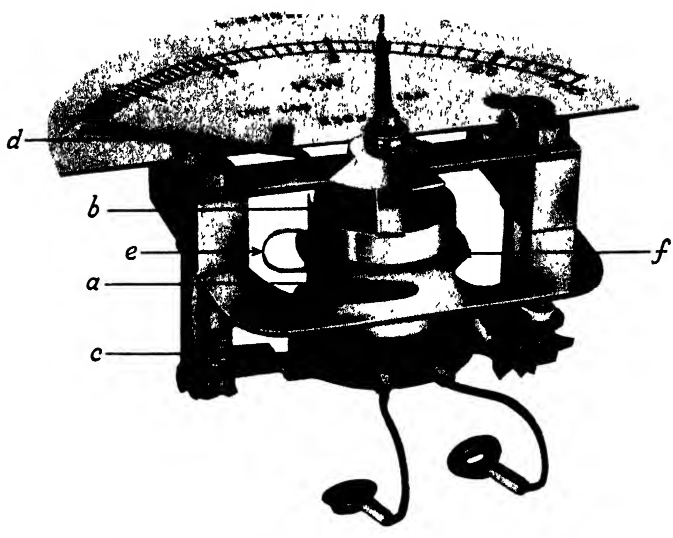


FIG. 154.—Movement of 'P & B' demand indicator.

the insulating material enclosing the heating element, and may be 15, 20 or 30 minutes. A characteristic curve showing the rate of increase in the indication on an instrument carrying a steady load and lagged to 30 minutes, is shown in Fig. 155. When the load on an indicator is increased from a steady low to a steady higher value, the time taken to indicate the higher value is the same as the time-lag of the indicator. Thus a 30 minute time-lag indicator will take 30 minutes to indicate an increase in load from a steady five amperes to a steady six amperes as shown in the illustration.

The "P and B" maximum-demand indicator is constructed to carry an overload of 20 per cent. and is scaled accordingly. The scale is 4¾

inches long, with a minimum reading of one-sixth of the maximum, e.g. a 5-ampere indicator reads 6 amperes maximum and 1 ampere minimum. The shape of the characteristic curve is the same for all current ratings having the same nominal time-lag, but differs slightly for instruments of the same current rating having different time-lags. The limits of error guaranteed by the manufacturer are: from maximum reading to half maximum scale value, within plus or minus 3 per cent.

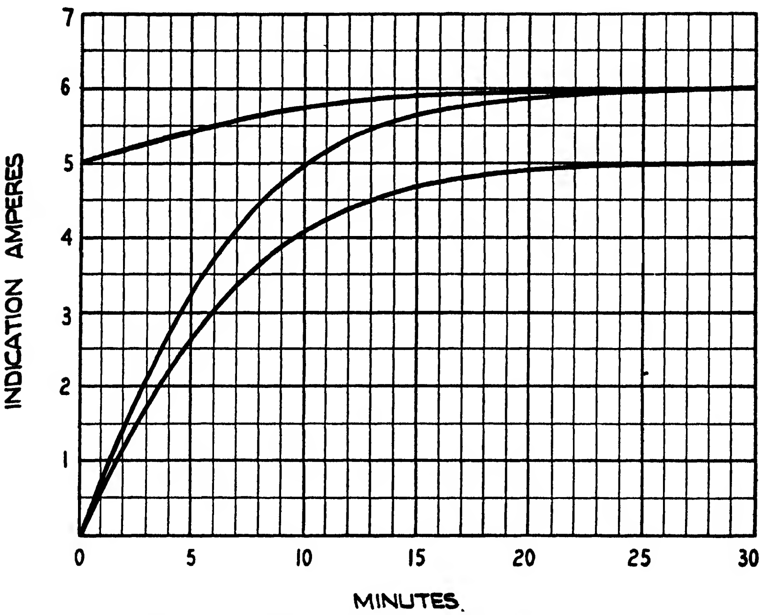


FIG. 155.—Characteristic curve for 'P & B' demand indicator.

expressed as a percentage of the indication. From half maximum reading to lowest reading, plus or minus 1·5 per cent. expressed as a percentage of the maximum scale value. The maximum pointer may be reset at the end of each assessment period by means of a knurled knob on the front of the case; the knob can be sealed or padlocked as required to prevent unauthorized use.

For the measurement of maximum demand in a three-phase circuit, a "P and B" maximum-demand indicator has been introduced comprising the combination of a single-element instrument with three

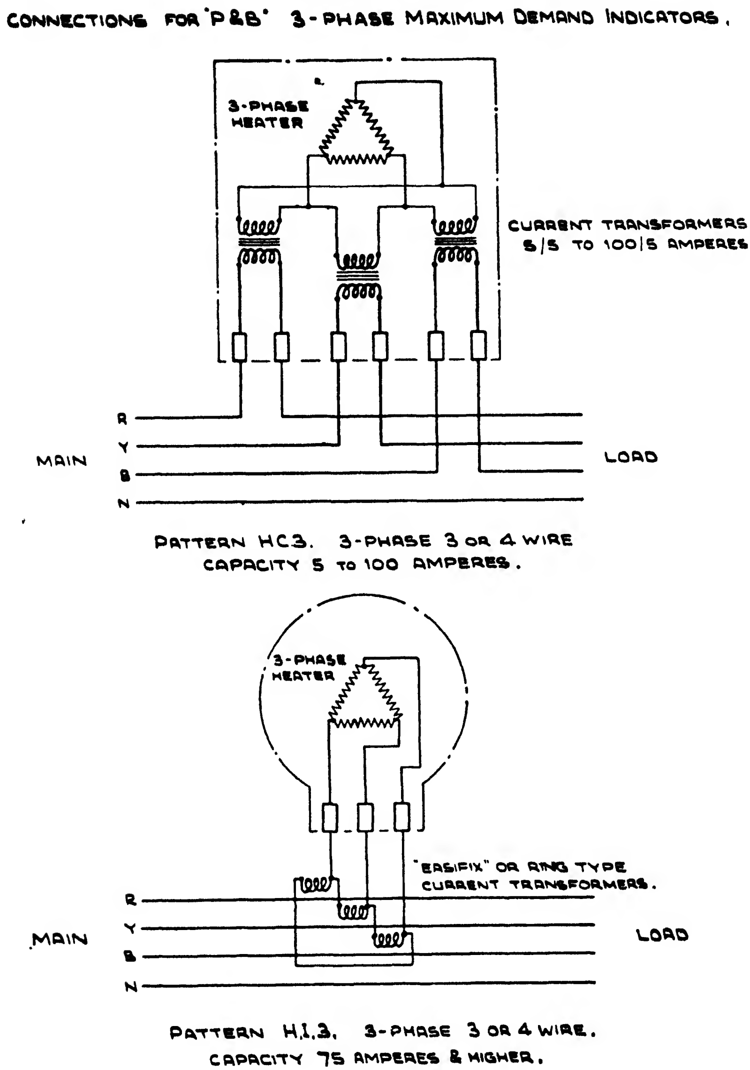


FIG. 156.—Connection diagram for 'P & B' three-phase demand indicator.

current transformers. The demand-indicator movement is similar to that already described, but is provided with a special three-phase heating element: the connections to this instrument are shown in Fig. 156.

It is made in two patterns, of which Type HC3 is self-contained with the current transformers in a sheet-steel case, and Type HI3 is arranged for connection to three transformers external to the indicator; the Type HC3 instrument is made in a range of standard ratings from 5 to 100 amperes. It will be noted from the diagram that the heating element and also the secondaries of the current transformers are delta-connected.

The limits of error for this three-phase demand indicator are the same as for the single-phase instrument provided that the load is

FIG. 157.—Metropolitan-Vickers maximum-demand indicator, integrating pattern.

balanced. If the load is unbalanced there is an additional small positive error, the magnitude of which depends upon the amount of out of balance. For example, when the load in two phases exceeds that in the third by 20 to 25 per cent. the additional error is of the order of 2 to 3 per cent.; with the load in two phases three times the load in the third, the error is of the order of 4 to 5 per cent. It is suggested by the makers that since the maximum demand during any assessment period normally occurs when the load is approximately balanced, any error due to badly unbalanced loads of comparatively low value is almost certain to be eliminated by a subsequent higher reading.

10.10. Metropolitan-Vickers Maximum-Demand Indicator. The Metropolitan-Vickers maximum-demand indicator is of the integrating type

and is a combination of a polyphase meter with a demand indicator mechanism. An illustration of a complete instrument is shown in Fig. 157. The meter, which has a separate energy register, can be supplied for connection in a three-phase three-wire or a three-phase four-wire circuit as required. The scale of the indicator is over 14 inches long and has 220 equal divisions at maximum indication. It is so ar-

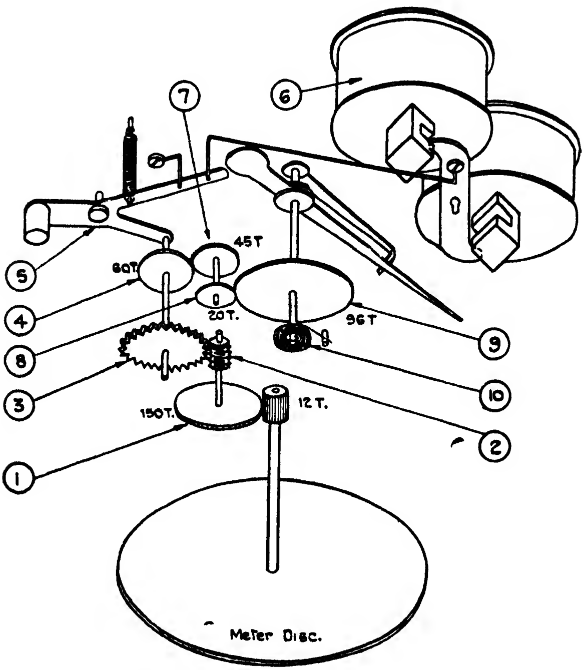


FIG. 158.—Perspective view of mechanism for Metropolitan-Vickers demand indicator.

ranged that on the marked full load of the meter, the pointer travels 200 divisions in one integration period; the maximum demand is determined by multiplying the indication in divisions by a suitable constant. The indicator can be geared for an integration period of 15, 20, 30 or 60 minutes. The indication is guaranteed by the manufacturer to be correct within plus or minus one scale division, that is, within plus or minus 0·5 per cent. of the full-scale reading at any point on the scale.

The general arrangement of the demand indicator mechanism and the method of operation will be understood by reference to the perspective drawing in Fig. 158. The rotor of the meter carries a pinion which drives through a train of gears (1), (2), (3), (4), (7), (8), (9), on to an arbor carrying a hairspring (10) at one end and a short driving pointer at the other end. Rotation of the meter disc causes the driving pointer to move round the scale, carrying with it the long double-ended demand pointer. At the end of each integration period, the length of which is determined by a suitable time switch and which may be, for example, 30 minutes, an electromagnet (6) is energized for a few seconds. The rotation of its armature causes the rocker arm (5) to move wheel (4) out of engagement with wheel (7) and the succeeding wheels (8) and (9) from the driving mechanism and permits the hairspring (10) to return the short driving pointer to the zero position. The long maximum-demand pointer does not return, but is retained by a friction device to mark the position to which it has been pushed.

At the end of the resetting interval (5 to 12 seconds), the electromagnet (6) is de-energized, the wheels (4) and (7) re-engage, and the driving pointer is again advanced by the meter. The indication of the maximum-demand pointer will be increased only when the average demand during an integration period exceeds that of a previous period; thus, the position reached by the maximum-demand pointer after a succession of integration periods will be an indication of the highest average load experienced during any one of the previous integration periods. At the end of a demand assessment period, e.g. three months, the maximum-demand pointer may be returned to zero without opening the meter case by pushing inwards and then turning a knurled plunger which is mounted concentrically with the axis of the demand pointer, in the glass window of the meter. Unauthorized resetting is prevented by sealing the plunger after use, by means of a wire and a lead seal.

10.11. Sangamo-Weston Maximum-Demand Indicator. The Sangamo-Weston maximum-demand indicator is of the integrating type, and the mechanism can be fitted to a standard Sangamo single-phase or polyphase meter. A front view of the mechanism is shown in Fig. 159, from which it will be seen that the dial of the energy register is combined with the scale of the maximum-demand indicator. The scale, which shows the maximum demand in kW, occupies an arc of 300 deg. and is $8\frac{5}{16}$ inches long. Two pointers are provided, a long one which indicates the maximum demand and a short one associated with a small diameter scale near the centre of the dial. The short pointer is a driver which

makes an excursion starting from zero at the commencement of each integration period and returns to zero at the end of the period. Together with the short scale, it permits a reading to be taken if desired at the end of each integration period of the average demand during that period. The long pointer is pushed forward by the short one and remains at the highest position to which it has been pushed in any period.

A separate time-switch is unnecessary with this demand indicator, as a timing element in the form of a small synchronous motor is in-

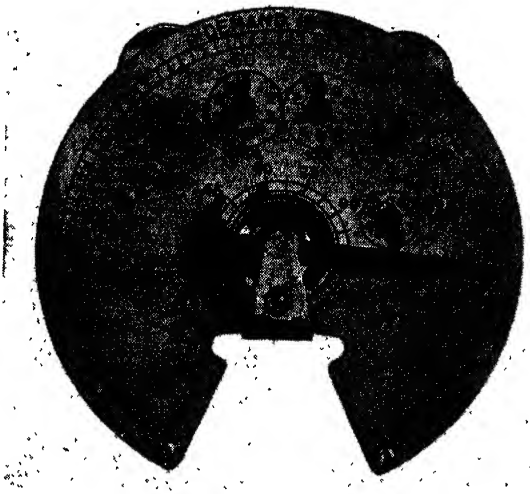


FIG. 159.—Sangamo-Weston maximum-demand indicator movement.

corporated in the mechanism. A rear view of the energy register together with the motor attachment is shown in Fig. 160. The motor drives through appropriate gearing on to two cams revolving at different speeds; the cams have segments cut out of their peripheries and when the openings come into coincidence at the end of each integration period, a pin drops and disconnects the short pointer from the driving-gears, thus allowing the pointer to return to zero under the action of a helical resetting spring. After the pointer has reached zero the gearing connection is restored and the cycle of operations recommences. The demand mechanism is made for standard integration periods of 15, 30

and 60 minutes. The glass window of the meter is drilled to take a manual reset device for use at the expiration of each demand assessment period and this reset can be sealed to prevent unauthorized use.

10.12. Aron Maximum-Demand Indicator. The maximum-demand indicator for kW maximum demand manufactured by Aron Electricity Meter, Ltd., is of the integrating type and possesses a number of novel features. The mechanism can be supplied as a self-contained unit,

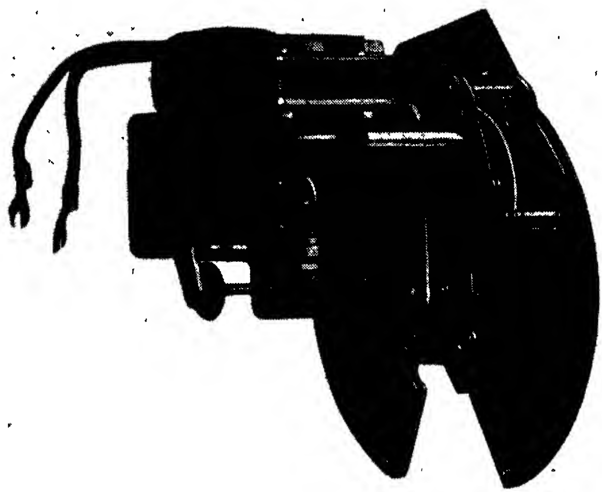


FIG. 160.—Rear view of Sangamo-Weston demand indicator mechanism.

complete with synchronous-motor driven tripping device, or alternatively arranged for tripping from an external time-switch. In the latter case an electromagnet, energized periodically through the time-switch, takes the place of the synchronous motor and its associated gearing, the meter-operated gearing being the same in both cases. The type referred to in the following description is the self-contained unit, a front view of which is shown in Fig. 161. The length of the scale is approximately 11½ inches, and all dials indicate directly the maximum demand in kW without the use of a constant.

The mechanism comprises two principal wheel trains, the arrangement of these being shown in Fig. 162. The main drive from the energy

element is through the worm (*1*) mounted on the rotor-shaft, and through gearing (*2*), (*3*), (*4*), (*5*), (*6*) and (*7*), to the non-return demand pointer (*11*). The drive from the fly-back wheel (*7*) to the pointer (*11*) is communicated through a thin wire arm, having a small indicator flag (*12*) attached thereto, and shown separated from the pointer in Fig. 161. The pinion (*6*) is driven by the shaft (*5*) through a spring friction-clutch at the forward end of the shaft. This clutch permits the pointer to be

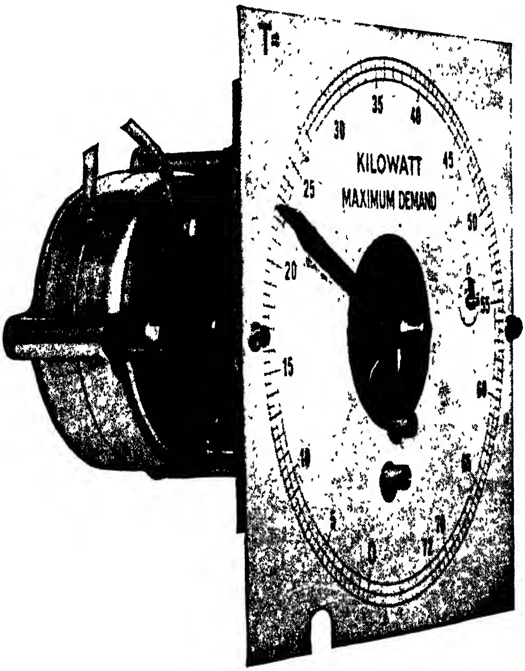


FIG. 161.—Aron maximum-demand indicator movement, front view.

set back manually to zero without disengaging the gears, and without damage to the teeth of any of the wheels.

The synchronous-motor drive to the tripping mechanism is through suitable speed-reduction gear (not shown in diagram) to the worm (*13*) and thence through gearing (*14*), (*15*), (*16*), (*17*), (*18*) and rotary arm (*19*), pinion (*20*) and tripping click (*21*). Pinion (*20*) engages in the periphery of the fixed wheel (*22*), so that as the arm (*19*) revolves with the wheel (*18*), the pinion and the tripping click with it are thereby

made to revolve on their own axis at a speed five times as great as the rotational speed of the arm. The actual tripping takes place when the arm (*19*) brings the pinion (*20*) into the neighbourhood of the tripping arm (*8*), so that the revolving tripping click (*21*) comes into contact with the extremity of the tripping arm and in passing, deflects the whole arm on its bearing (*9*), thus disengaging the pinion (*6*) from the fly-back wheel (*7*).

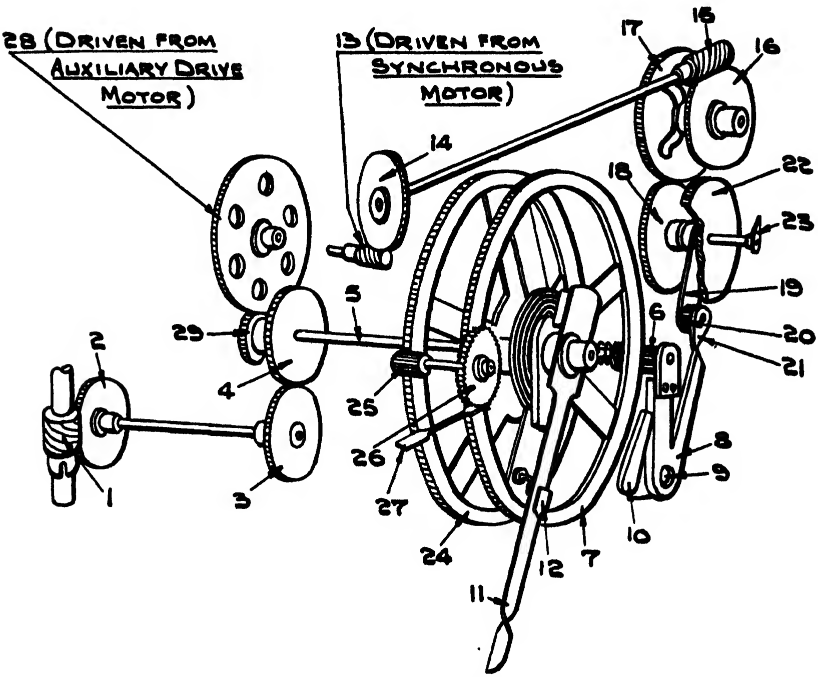


FIG. 162.—Arrangement of gearing in Aron demand indicator.

The fly-back wheel when driven forward by the energy element winds up a hairspring, and when disengagement of the gears takes place, the tension on the hairspring restores the fly-back wheel together with its flag arm (*12*) to its initial position at zero. The period of disengagement, or the resetting interval, may be adjusted between the limits of 3 to 12 seconds approximately, but 6 seconds is the usual period for a 30-minute trip. The adjustment is made by altering the angular setting of the fixed wheel (*22*) on its axis, thus altering the effective radius to the tip of the tripping click (*21*) at the instant when

it establishes contact with the tripping arm (*8*). By turning the screw-head shown in Fig. 161, a fine adjustment of the zero position of the flag-arm can be effected, and adjustable stop-piece (*10*) is provided so that the depth of engagement between the pinion (*6*) and the fly-back wheel can be set correctly.

The drive from wheel (*16*) to wheel (*17*) on the same shaft, is through a friction clutch. The object of this arrangement is to enable the wheel (*18*) to be turned by hand in order to advance, if desired, the phase of the integration period for testing, synchronizing or other purposes. The index (*23*), (shown also in Fig. 161), makes one revolution during each integration period and enables the phase of the tripping to be observed.

To ensure stability of the pointer (*11*), a novel form of assembly is provided. The wheel (*24*) which is rigidly secured to the same arbor as the pointer, drives a pinion (*25*) mounted on the same arbor as the saw-tooth wheel (*26*). The free end of a light spring (*27*) rests on the saw-tooth wheel; this acts as an effective brake and prevents any movement of the pointer as a result of vibration. At the same time it offers a very small resistance to the movement of the pointer when being driven by the fly-back wheel; the latter is mounted loosely and revolves freely on the arbor carrying the pointer. The gear ratio between the arbors carrying the pointer and the saw-tooth wheel respectively is such that there are 576 tooth movements of the spring for one complete revolution of the pointer. This means that one tooth movement of the saw-tooth wheel, which is the minimum jump, corresponds to a very small movement of the pointer, thus permitting great accuracy of indication at very low-scale readings.

The mechanical burden which would normally be imposed on the energy element when driving the demand indicator mechanism is relieved, if not entirely eliminated, by means of a small Ferraris induction motor which takes over this duty. The motor, which is constantly energized, is connected through a light spring coupling to the wheel (*28*) and so drives wheel (*29*) fixed at the rear end of the main drive spindle (*5*). The torque of the auxiliary motor is low, but is regulated to be just sufficient to turn all the wheels of the main drive immediately this is permitted by any forward movement of the meter rotor. When the latter is stationary, the auxiliary motor cannot drive the gearing because this is locked by the engagement of the worm wheel (*2*) with the worm (*1*) on the meter rotor.

The advantage claimed by the manufacturers for the foregoing

arrangement is that the accuracy of the meter to which the mechanism is attached is entirely unaffected at any load. It is stated that the meter can be calibrated in the absence of the demand indicator mechanism and the calibration will still hold good when the mechanism is subsequently fitted. There is no necessity for extra forward creep adjustment

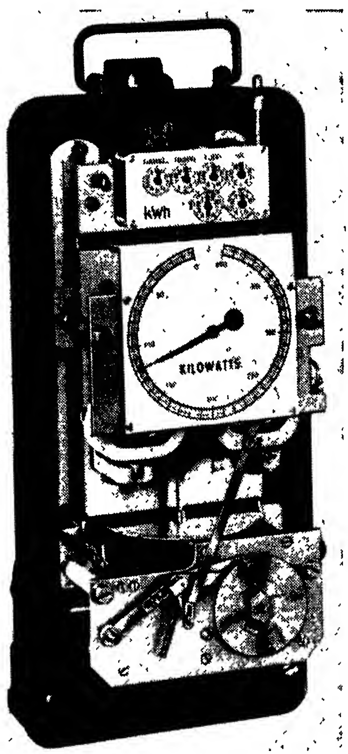


FIG. 163.—Chamberlain & Hookham maximum-demand indicator with self-contained timing element.

in order to obtain reasonable accuracy at low loads. The constant forward torque exerted by the auxiliary motor takes up all backlash in the wheel train of the main drive and this is conducive to a high degree of consistency in repetitive readings of the demand indicator.

10.13. Chamberlain and Hookham Maximum-Demand Indicator. The Chamberlain and Hookham maximum-demand indicator is an instrument of the integrating type and is made for the measurement of

maximum demand in kW, kVA or reactive kVA in polyphase circuits. The kVA instrument is arranged for a restricted range of power-factor, either 0·5 to 0·9 or 0·8 to unity, as desired. The metering portion may have two, alternatively three measuring elements according to requirements and the demand indicator may be arranged for operation in conjunction with an external time-switch or a self-contained timing element. An illustration of a three-phase four-wire kWh meter, Type JT4S, with the front cover removed, having three measuring elements, combined with a kW maximum-demand indicator and self-contained timing element, is shown in Fig. 163. This instrument is an example of one in which the energy register, the demand indicator and the timing element are in the form of three separate units.

As will be seen from the illustration, the kWh register is of standard construction and can be removed for examination if desired without disturbing the demand indicator. The register is self-locating on the meter and is secured by a sliding catch projecting through the meter frame on the left of the register. The demand indicator, which is also self-locating, is supported by two pillars and secured thereon by two screws. A worm on the rotor shaft drives a worm wheel mounted on a horizontal shaft in the demand indicator mechanism. A pinion on the worm-wheel shaft drives through an idle wheel on to a second pinion mounted on a second worm-shaft. The worm on the latter drives a fly-back wheel which constitutes the final wheel in the train; one end of the second worm-shaft is supported by a pivoted counterweighted lever which normally retains the worm in engagement with the fly-back wheel. At the end of each integration period the counterweighted lever is actuated by the timing element (or by an electromagnet if a separate time-switch is employed), to disengage the worm from the fly-back wheel.

The fly-back wheel runs loosely on a short stud carried on a supporting bracket, and a hairspring tends to retain the wheel against a zero stop pin on the same bracket. Co-axial with and adjacent to the fly-back wheel is a large diameter ratchet wheel having 360 teeth. This wheel is mounted on a short arbor projecting through the front plate of the mechanism, and carries the maximum-demand pointer on its outer extremity. A short driving peg projecting from one face of the fly-back wheel engages a corresponding peg projecting from the opposing face of the ratchet wheel, and when the fly-back wheel is driven in the forward direction by the meter rotor the ratchet wheel is pushed forward by a corresponding amount. At the end of each integration period, when the second worm is disengaged from the fly-back

wheel, the latter is restored to the zero position by the tension on the hair spring. The ratchet wheel, which has a light leaf-spring resting on its periphery, remains in the position to which it has been pushed. After a succession of forward excursions of the fly-back wheel, the position of the maximum-demand pointer will indicate the maximum demand which has occurred. To guard against the possibility of the meter becoming jammed or the demand indicator becoming damaged in the event of a failure in the time-switch or timing element, a few teeth are omitted from that portion of the fly-back wheel which is in engagement with the worm after the full-scale reading has been passed. It will be appreciated that a stoppage of the time-switch, or a failure to send a resetting impulse, may result in the demand pointer in any demand indicator being driven beyond the full-scale position; in the absence of any safety device, the teeth might be stripped off the wheels in the mechanism or the meter might be stopped. The omission of teeth from the fly-back wheel at the appropriate point permits the meter to run indefinitely after the full-scale position has been passed, as no further advance of the pointer can then take place.

The reset of the pointer to zero at the end of a demand assessment period is accomplished by means of a button which projects through the right-hand top corner of the meter case. This is shown in the illustration immediately above the energy register, and is attached to a push-rod which, when depressed, lifts the leaf-spring off the periphery of the ratchet wheel; a hairspring attached to this wheel causes it to return to the zero stop. The same movement of the push-rod also disengages the worm and fly-back wheel and the latter returns to zero simultaneously. A sealing hole through the projecting button permits the insertion of a sealing wire to prevent unauthorized operation.

The self-contained timing element is shown in the illustration, below the demand indicator. The whole of the mechanism is mounted on a baseplate supported on two pillars and secured by two screws. It consists of a train of wheels driven at one end by a small synchronous motor and arranged behind the baseplate. The gear train terminates in an arbor which projects through the plate, and carries a timing disc on its forward extremity; the timing disc, which rotates in a clockwise direction, makes one revolution per hour and in the example shown has two trip pins arranged at diametrically opposite points, thus, tripping of the mechanism will occur at 30-minute intervals.

A cranked lever, pivoted at the extreme left of the baseplate, is arranged so that its free end is lifted by each trip pin in turn and allowed

to fall as it passes. A heavily-weighted L-shaped lever is carried by the cranked lever and swings on pivots about half-way along the latter. The long arm of the L-shaped lever lies more or less horizontally and is also lifted by the trip-pins. The tip of the cranked lever extends slightly beyond the tip of the L-shaped lever, with the result that the latter falls off the trip-pin first, followed a few seconds later by the cranked lever. The illustration shows the position after the fall of the L-shaped lever and before the fall of the cranked lever. The pivots for the L-shaped lever are set eccentrically in a friction-tight bush which when turned, serves to alter the effective length of the horizontal arm of the lever. By this means the relative positions of the tips of the levers can be adjusted very accurately and the resetting interval can be determined to a fraction of a second.

The mechanical connection between the timing element and the demand indicator consists of a long tripping lever pivoted just below the lower edge of the demand indicator and extending downwards to the vertical arm of the L-shaped lever. A pivot pin at the extremity of the latter passes through a vertical slot in the tripping lever and can move freely in a vertical direction without moving the tripping lever; when however, the L-shaped lever falls off the trip-pin on the timing-disc the vertical arm swings over to the left, carrying with it the lower arm of the tripping lever. The uppermost portion of the tripping lever is moved to the right, and lifts the worm out of engagement with the fly-back wheel in the demand indicator mechanism. Two or three seconds later the tip of the cranked lever on the timing element also falls off the trip-pin, allowing the L-shaped lever to revert to its normal position and the tripping action is terminated.

The arbor on which the timing disc is mounted also carries a friction-plate against which adjustable spring tension is applied. This entirely eliminates backlash and the movement of the trip-pins is progressive in the forward direction, undisturbed even by severe vibration. It also permits the adjustment of the resetting interval to be made with great accuracy and assures the maintenance of the original setting; the interval can safely be reduced to three seconds and the error due to a long resetting interval is eliminated. A friction drive between the timing disc and the arbor on which it is mounted permits the timing disc to be turned by hand for testing purposes or for adjusting the phase of the resetting interval.

10.14. Influence of the Duration of the Integration Period. The duration of the integration period in the case of integrating instruments, or the

time lag in the case of thermal instruments, may exercise considerable influence on the maximum demand indication; in practice a thirty-minute period is standard for most tariff purposes. Thermal instruments which are used extensively for obtaining a record of the maximum loading on feeders, power transformers, motors and the like, may have a time-lag extending to three hours. The characteristic of a thermal instrument is such that under steady load conditions, 90 per cent. of the maximum indication may be reached during one-quarter of this time and 99 per cent. during two-thirds of the time. It is important therefore, to bear in mind the difference in characteristics when comparing the indications of a thermal and an integrating instrument, and to remember that in the latter, the rate of increase in the indication is directly proportional to time.

Where the load is maintained at a steady value for long periods, the maximum indications on instruments having different integration periods or time lags will be alike. Where the load is unsteady and includes pronounced peaks of short duration these peak loads may be completely registered on instruments having short integration periods and only partly registered on those having long integration periods. If it is the desire of the supply authority to discourage loads with short peaks, then a short integration period may sometimes be justified. This justification would depend to some extent upon the frequency with which the demand indicator is reset to zero. If resetting takes place monthly and the consumer is charged according to his maximum demand during that month only, then the penalty for a peak of short duration may not be unwarranted, but if the reset is made annually, the penalty for what may have been a single peak load during the year may amount to an imposition if it results in a heavy charge for the whole period.

Mention has been made of the possibility of failure in the case of an integrating instrument to register a maximum demand, the duration of which does not exceed that of the integration period. If normally a steady load of say 90 kW is maintained and on one occasion the load is increased to 100 kW for thirty minutes, then the demand indicator should respond by indicating 100 kW, assuming that it has a thirty-minute integration period. But if the increase in load occurred half way through an integration period, the average load during that period would be 95 kW, and this would be the indication on the dial. During the succeeding integration period, the load would be 100 kW for fifteen minutes, followed by 90 kW for fifteen minutes. Thus the average

load would again be 95 kW and no further advance in the indication would occur. This condition could arise only if the increased load was divided equally over two integrating periods which would be a coincidence. It is more probable that the division would in fact be unequal in which case an indication greater than 95 kW would be shown and the maximum possible error would be reduced. A thermal instrument would indicate 100 kW in a case such as this, irrespective of the time when the increase in the load occurred.

10.15. Factors which Influence Accuracy in Maximum-Demand Measurement. There is no standard specification current in this country which deals with maximum-demand indicators and the errors incurred in maximum-demand measurement. In B.S. 37: 1937, Clause 37, brief reference is made to the effect of a demand indicator mechanism on the error of the integrating meter to which it is attached, but this specification does not deal with the errors of the demand indicator as such. The British Standards Institution which is the body to which one looks naturally to undertake the publication of a suitable specification did in fact take the initial step towards its preparation in 1939, but the outbreak of World War II resulted in its postponement. For various good reasons, resumption of this preparatory work was delayed, but in view of the increasing importance of maximum-demand metering and tariffs it is to be hoped that publication of a specification will not be long delayed.

Because of the lack of an agreed standard defining the errors of maximum-demand indicators, such information as is available from the manufacturers of these instruments cannot readily be used for comparative purposes. Each manufacturer is at liberty to express the errors of his production in the manner appearing to him appropriate and in some instances this may lead to incorrect inferences being drawn. Apart from the errors which are inherent in all types of maximum-demand indicator, errors of observation must also be taken into account. The accuracy with which a reading can be taken varies in different instruments and the error of observation is something quite distinct from the error of the instrument being observed; its magnitude is associated to some extent with the scale length, the pointer length and also the form of the scale. If the scale is uniformly divided throughout its length it is easier to estimate visually the value of a fraction of a division than is the case where the divisions are progressively diminishing in size. Instruments of the types which have been described in earlier paragraphs have scales varying in length from 4½

inches to 14 inches or thereabouts. It is not easy to assign a value to an error of observation as much depends upon the observer, but it will doubtless be agreed that the error in observing a 14-inch scale should be substantially smaller than in observing a 4½-inch scale, other things being equal.

It may be noted here that it is customary to specify the error of a demand indicator, as of any other indicating instrument, in terms of a percentage of the full scale reading. This is particularly important when considering readings taken near the bottom of the scale. An error of one per cent. of the full-scale reading at one-fifth of full scale is equal to an error of five per cent. in the indication. In other words, if full-scale reading is 100 kW, an error of one per cent. of full scale at one-fifth of full-scale indication is an error of 1 kW in 20 kW, or five per cent of the indication.

The scales of thermal instruments are non-linear, the spacing of the divisions being open at the top and contracted at the bottom; this makes it possible to read the upper portion of some thermal instrument scales within an error of observation comparable to that in reading an integrating instrument having a scale nearly twice as long. On the other hand, for readings below about ninety per cent. of full-scale, the thermal instrument is usually much inferior to the integrating instrument in this respect.

Because of the non-linear scale in thermal instruments there is a greater possibility of scale errors than in integrating instruments. In some thermal instruments a number of points on the scale may be determined by actual test and the intermediate divisions filled in by a manual sub-dividing process. In others a printed scale may be used conforming to the average indication of a number of instruments, a process which ignores individual errors. On the other hand, integrating instruments follow a straight-line law and this permits printed scales to be used, the uniform subdivision being carried out with great accuracy.

Mention has already been made of errors inherent to thermal maximum-demand indicators when operating under unfavourable conditions. Since this class of instrument is actuated by current values only it can only be used for tariff purposes where the tariff is based upon the current in amperes flowing in the consumers' circuit. This is seldom the case as tariff charges are usually based upon the load in kW or kVA. To meet this requirement thermal demand-indicators are scaled in terms of kW or kVA at the declared voltage of the supply to

which they are connected. Any departure from the declared voltage at the time the maximum demand is registered results in an error in the indication, this error being positive for a reduced voltage and negative for an increased voltage; the magnitude of the error is of the same order as the percentage departure from the declared voltage.

If the tariff is based upon the load in kW, a further error will arise should the power-factor depart from unity. The power-factor of the domestic consumer's load is usually unity or thereabouts so that no error would arise in this case, but the industrial consumer's load is seldom in the region of unity and in these circumstances substantial errors may be anticipated. However, industrial loads are usually three-phase, and the tariffs for these are frequently based upon kVA loading. Three-phase thermal demand-indicators are available for this purpose and are calibrated for use at the declared voltage of the supply, but these instruments are subject to error if the load is unbalanced.

In the case of integrating instruments the accurate measurement of the integration period is important. The measurement may be effected by means of a separate spring-driven time-switch having escapement control, or by a time-switch driven by a synchronous motor. Alternatively a self-contained timing element such as has been described in previous paragraphs may be incorporated in the meter. Where a time-switch is used, a pair of contacts are closed (or opened) periodically to control the tripping of the demand indicator mechanism. The error in time-keeping of an escapement-controlled time-switch is usually so small as to be of negligible importance, insofar as the length of the integration period is concerned. If, however, the time-switch is driven by a synchronous motor, any departure from the normal frequency of supply at the time of maximum load will affect the accuracy of the maximum-demand measurement. A one per cent. reduction in supply frequency at this time would result in a one per cent. increase in the duration of the integration period and a corresponding over-registration of the maximum demand. A self-contained motor-driven timing element would of course be affected in a similar manner.

The closure of the tripping contacts or the actuation of the tripping mechanism is usually effected by a trip-pin on a rotating disc, driven at a constant speed by the time-switch or timing-element. This disc may make one revolution in each integration period, but it is also a common practice to arrange the gearing so that the disc makes one revolution per hour. This latter arrangement is convenient as it permits

the same gearing to be employed for any of the usual integration periods. The disc may carry one, two, three or four equally spaced trip-pins, corresponding to 60, 30, 20 or 15-minute integration periods respectively. The accurate spacing of the pins is important as any error in this respect will result in variation in the length of the integration periods with a corresponding possibility of the maximum-demand registration being in error.

At the end of each integration period comes the resetting interval, the short period during which the demand indicator mechanism is restored to zero and wherein no registration takes place. This interval should be kept as short as possible consistent with ensuring that complete reset has taken place. One or two seconds is usually ample for this purpose, but after the time-switch has been in commission for a few years, the effects of wear on its tripping levers may result in a slight increase or decrease in the set time. The interval is usually determined by two levers, the tips of which fall off the trip-pin in succession, one lever being slightly shorter than the other. The resetting interval is the interval which occurs between the fall of the first lever and the fall of the second, and a fine adjustment is usually provided on one lever to enable this to be set with exactitude. To allow for wear on the tips of the levers, a minimum interval of five seconds may be desirable in some cases. If vibration is present, a shorter interval may increase the risk of both levers falling simultaneously, in which case no reset will take place; following such an occurrence the integration period would be doubled and if this occurred when the load was substantial, a fictitous maximum demand would be registered.

The resetting interval, if too long, may introduce an appreciable error in the maximum-demand indication since it represents a reduction in the integration period. For example, a 9-second interval in a 30-minute period (1,800 seconds), is equal to a reduction of 0·5 per cent. on the maximum-demand indication. This error may be eliminated by arranging the gearing of the demand indicator to over-register by a percentage equal to the percentage of the integration period occupied by the reset.

Backlash in the gearing may be responsible for a small error of under-registration. Occasionally after the mechanism has been reset, a short period may elapse before the drive from the meter is communicated to the driving pointer; usually the loss in registration is so small as to be negligible and in any case is unlikely to exceed 0·5 per cent. of the full-scale reading. If however, the maximum-demand reading is

only a small fraction of the full-scale reading, the error may cease to be negligible; backlash error is caused through undue freedom at the points where meshing of gears takes place. It is difficult to eliminate entirely since tight gearing will cause undue friction in the mechanism and will result in under-registration on the part of the integrating meter.

The total error in a maximum-demand reading on an instrument of the integrating type is the sum of the errors of the integrating meter, the demand indicator mechanism, and the timing element or time-switch, all at the actual time when the maximum demand occurred. These may be cumulative, but insofar as they consist of errors of plus and minus sign, they will tend to cancel out. As regards the integrating meter, the only error of importance in this connection is the error at the load indicated on the instrument. In the case of a kVA meter arranged for a restricted range of power-factor, the only error of importance is that at the particular power-factor existing when the actual maximum demand occurred. The fact that the meter may have considerable errors at power-factors outside its range is of no consequence. This subject is considered at greater length in the previous chapter dealing with kVA meters.

In comparing the possibilities of error arising in different types of instrument as detailed in the preceding paragraphs, it would appear that thermal instruments may be suitable for the measurement of maximum demand for statistical or record purposes, where accuracy under varied operating conditions is not of first importance. They may also be suitable for ascertaining the state of balance of the load on three-phase feeders by the insertion of a single-element instrument in each phase. For tariff purposes, however, the majority of supply undertakings show a preference for an instrument of the integrating type, as it is independent of voltage variations over a wide range and usually is not affected by unbalanced loading.

A further important point is that where duplicate instruments are installed for check purposes, integrating instruments by different manufacturers may be expected to be in agreement provided that the integrating periods are in phase. Thermal instruments supplied by different manufacturers may fail to be in agreement because of their differing characteristic curves, notwithstanding the fact that the instruments are in perfect working order. Thermal instruments will almost certainly indicate a higher value than an integrating instrument if the load during the period in which the maximum load occurred

was of a variable character. Even so, the integrating instrument is not beyond reproach as its accuracy is not of the same high order as that of an integrating meter, but in the present state of the art it is probably the best that can be achieved. It has the redeeming feature that such errors as may be incurred are usually in favour of the consumer, whereas the errors of a thermal instrument are more often in favour of the supply authority, and as such, cannot be defended in the event of a disputed account.

CHAPTER XI

SUMMATION METERING

11.1. Objects and Methods of Summation Metering. When it is desired to measure the total load on two or more circuits, summation metering is adopted. The object of summation metering is not necessarily to obtain the total consumption in a number of circuits because this can be determined quite simply by arithmetical means. Usually the object is to arrive at the maximum demand over a period of time or to obtain a record of the variation in the demand. In the case of maximum demand, it is not sufficient to fit a demand indicator on each of the circuits feeding a particular concentration of load and to add together the readings of all the indicators since the maximum demand may not occur on each circuit simultaneously. In such a case the arithmetical sum of the demand indicator readings would give a figure possibly much in excess of the actual maximum demand.

The method adopted for obtaining the simultaneous maximum demand on a number of circuits will depend to a certain extent on the number of circuits to be summated and upon the accuracy desired in the measurement. Questions of cost will be an important factor in small installations of a few hundred kilowatts, but the cost of an elaborate scheme may be insignificant when dealing with the output of a large generating station or a bulk supply to an undertaking distributing over a large area.

Of the various systems of summation metering which have been used, the following are the most important.

1. An energy meter is provided with multiple current-windings, each of the circuits to be summated having its own winding.
2. A number of meter elements, one for each circuit to be summated, are arranged to operate on a single rotor system having an appropriate number of driving discs.
3. A number of meters, one for each circuit to be summated, are coupled together through a system of differential gears and drive on to a single register.
4. A number of current transformers, one for each circuit to be summated, have their secondary coils connected in parallel and

the total secondary current is fed through the current coil of an energy meter.

5. A number of current transformers as in 4 have their secondary coils connected to an auxiliary transformer (known as a summation transformer) provided with an equivalent number of primary windings. The secondary of the summation transformer is connected to the current coil of an energy meter.
6. A number of meters, each fitted with a contact-making device actuated by the rotor, are connected, one in each of the circuits to be summated. The contact-making devices are connected to an instrument which is adapted to register electrical impulses received from the originating meters.

Of the foregoing, numbers 1 to 5 are only suitable for use where a small number of circuits are involved and usually their sphere of usefulness is limited. On the other hand, number 6 can be used for a large number of circuits and where considerable distances separate the points at which the energy is being measured. It can also be used to summate A.C. and D.C. supplies. Each of the systems referred to can be elaborated and two or more systems can be combined with advantage in certain circumstances.

Summation metering methods may be divided into two categories, the first in which the measurement of the electrical quantity in each of the circuits and its summation is carried out in a single instrument or in a transformer connected to a single instrument and the second in which each circuit is provided with a measuring instrument having means for initiating electrical impulses which are registered and summated in a separate device. The measuring instruments and other devices used in summation metering may be defined as follows:

1. An Impulsing Meter is a meter fitted with a contact-making device adapted to close an electric circuit each time a predetermined quantity of the commodity being measured has passed through the main circuit in which the meter is connected.
2. A Summation Meter is a meter having two or more sets of current windings or elements, each of which is connected in a separate circuit. Alternatively, a meter having one set of current windings adapted to measure currents proportional to the vector sum of the currents in two or more circuits. The total registration

of the meter is the sum of the registrations due to the passage of current in the individual circuits.

3. A Summation Transformer is a current transformer having two or more primary windings each of which is connected in a separate circuit. The current in the secondary winding is proportional to the vector sum of the currents in the primary windings. The primary windings may, if convenient, be connected directly in the circuits which are to be summated, or alternatively may be connected to the secondaries of other current transformers, the primaries of which are connected in the circuits to be summated.
4. A Summator is a device adapted to register electrical impulses initiated by two or more impulsing meters. The total number of impulses registered is a measure of the total consumption in the circuits to which the impulsing meters are connected. A summator may have a separate register corresponding to each impulsing meter and a register on which is shown the sum of all the impulses received. In addition, a demand indicator showing the simultaneous maximum demand on all the circuits to which the impulsing meters are connected may be provided, although this may be dispensed with if a printometer or chart recorder is employed to give a separate record.

In practice, summation is usually confined to polyphase circuits, but there is no reason why single-phase summation should not be undertaken if required. Also, summation of kWh is referred to generally in this chapter but it is equally applicable to reactive kVAh if desired.

11.2. Summation Meter with Multiple-Current Windings. One of the simplest forms of summation meter consists of an ordinary kWh meter having two current windings on each current electromagnet. This is used where a supply is provided through duplicate feeders, both of which are normally energized but either of which may be disconnected without interrupting the supply to the substation or consumer. The current windings are so disposed on the electromagnets that with equal currents, the same driving force is exerted as nearly as possible. Under working conditions it is unlikely that both feeders will be fully loaded at the same time and consequently the maximum load on the meter will never be twice the maximum load which each feeder may carry. Accordingly the meter is designed preferably to operate under full load conditions when both circuits are carrying approximately 75 per

cent. of their full load. Such a meter would be capable of registering correctly when one circuit was fully loaded and the other one was disconnected. This ensures better performance on low loads than would otherwise be obtainable.

The connection diagram in Fig. 164 shows a two-circuit summation meter arranged to summate the load on two 3-phase 3-wire feeders.

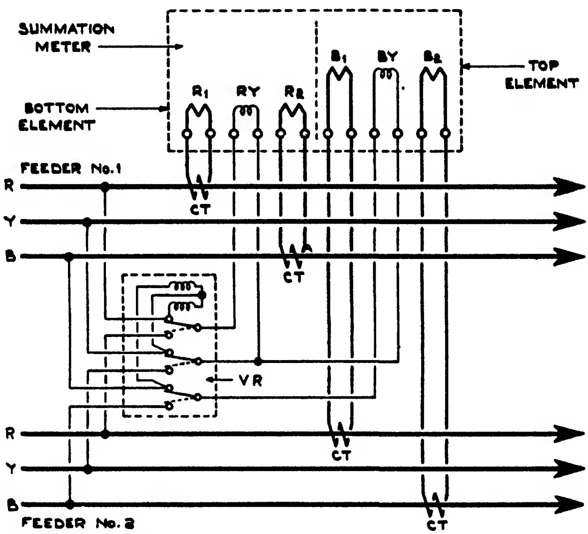


FIG. 164.—Connection diagram for two-circuit summation meter.

R1. Current coil in red phase. Supply 1.
R2. Current coil in red phase. Supply 2.
B1. Current coil in blue phase. Supply 1.
B2. Current coil in blue phase. Supply 2.
RY. Voltage coil between red and yellow phases.
BY. Voltage coil between blue and yellow phases.
CT. Current transformer.
VR. Voltage selector relay.

Each meter element has one voltage coil and two current coils, the latter being supplied through current transformers connected in corresponding phases in the two feeders. Since the two feeders are connected in parallel it is immaterial which is selected for connection to the voltage elements of the meter, but as one or the other feeder may occasionally be disconnected, provision must be made to ensure that the voltage elements are always connected to a live feeder. This is accomplished through the medium of a voltage-selector relay which

consists of a three-pole change-over switch and two voltage coils. The latter are connected to a feeder which is normally selected to energize the relay and in the diagram this feeder is No. 1. So long as No. 1 feeder is alive, the movable arm of the relay will connect the meter voltage coils to No. 1, but should the supply be interrupted, the movable arm will fall by gravity or spring action and contact will be established with No. 2 feeder. When the supply on No. 1 is restored the relay will again revert to the normal connection.

This method of summation is not limited to two circuits and can be extended to three or even four parallel circuits if desired. The limiting feature is the difficulty in accommodating a number of separate windings on a single current-electromagnet core, as space is usually restricted and each winding must be suitably insulated from its neighbour. A further difficulty lies in the necessity for each winding to produce the same driving torque with the same current. The position of each winding on the core is very important and if one succeeds in achieving equality in performance on non-inductive loads it will frequently be found that there is a difference in performance on inductive loads. No practical method of adjusting any inequality has been devised and consequently it is necessary to extend the permissible limits of error which are applicable to ordinary meters. This extension is in the form of a tolerance which varies according to the number of circuits for which the meter is constructed. The usually accepted tolerance for each circuit in excess of one, is $\pm$ 0·5 per cent. for loads between 125 per cent. and 20 per cent. and $\pm$ 1·0 per cent. for loads below 20 per cent. down to 10 per cent. The load refers to current expressed as a percentage of the total current in all the circuits when each is fully loaded. The voltage-selector relay must be such that it can select from any one of the circuits to which the current coils are connected.

11.3. Summation Meter with Multiple Elements. An ordinary three-phase three-wire meter having two single-phase elements acting on one rotor may be regarded as a summation meter which adds together the consumption in two separate circuits. In the same way, a three-phase four-wire meter may be regarded as a three-element summation meter. This principle may be extended to cover a larger number of elements and it is not difficult to construct a summation meter having the equivalent of two three-phase four-wire elements or three three-phase three-wire elements. Such a meter would have four discs mounted on one spindle, three of the discs having two single-phase driving elements on each and the fourth disc having a number of permanent

magnets acting upon it to provide the required brake-force. The six single-phase elements must each be independently adjustable so as to produce equality in driving torque at any particular load. Care must be taken to ensure freedom from interaction between elements, in view

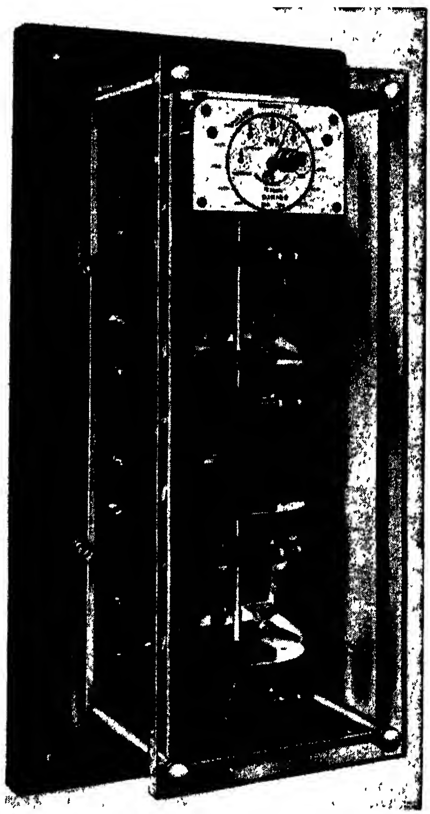


FIG. 165.—Metropolitan-Vickers two-circuit summation meter.

of the close proximity of the elements to one another and to the fact that two elements act on each driving disc. A summation meter made by Metropolitan-Vickers having four separate single-phase elements, each acting upon a separate disc and having four brake magnets is shown in Fig. 165. This meter is suitable for summating the load in two three-phase feeders.

The practical limit to the construction of a summation meter of this type is eight single-phase elements, which suffice for summating four three-phase circuits. The weight of the rotor is considerable, particularly in view of the fact that the shaft has to be made disproportionately large in order to ensure the necessary rigidity. As a consequence the rate of wear on the bottom bearing must be expected to be considerable and replacement of the bottom pivot and jewel will have to be made at intervals more frequent than is found necessary in an ordinary meter, if a reasonable degree of accuracy is to be maintained.

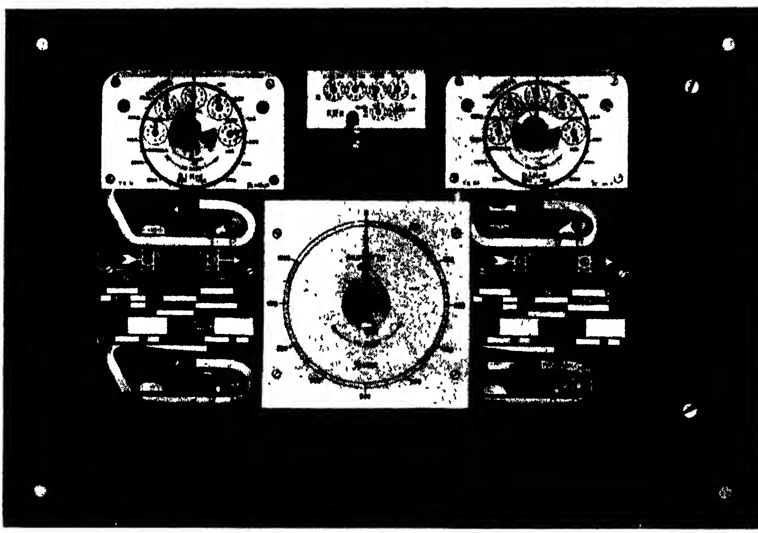


FIG. 166.—Metropolitan-Vickers summation meter having two coupled metering elements.

A summation meter with multiple elements has certain advantages over a meter with multiple current windings in that the circuits to be summated may have different voltages, different frequencies or may be out of synchronism. Since each current winding has its associated voltage winding, the voltage selector relay can be dispensed with. The kilowatt rating of each element must of course be the same and with careful calibration, a reasonable degree of accuracy can be achieved. On the other hand, a small error will be introduced if at any time one or more circuits are switched out, resulting in the voltage coils connected to these circuits becoming dead. Such an occurrence would

result in the remaining elements over-registering to the extent of perhaps 0·5 per cent. for each circuit disconnected. As this is unlikely to occur at the time of maximum demand, the probability of an error in the maximum demand reading is remote but the kWh registration would be affected slightly.

11.4. Summation Meter with Coupled Elements. A summation meter of simple construction and involving very little modification of standard parts consists in the coupling together by means of a differential gear of two polyphase meters. Each meter drives on to a sun wheel of a differential gear and the planet wheel which integrates the sum of the two movements communicates motion to an arbor at a rate proportional to the total power in the two circuits at any instant. This arbor drives on to a totalizing register and to a demand indicator giving the simultaneous maximum demand. A meter of this class made by Metropolitan-Vickers is illustrated in Fig. 166 and consists of two standard polyphase meters, each fitted with its own register and demand indicator. Between the two meters is a register giving the total consumption in the two circuits and a demand indicator giving the simultaneous maximum demand. Such an arrangement can be used on parallel feeders and is capable of a high degree of accuracy. Each meter is separately calibrated and its accuracy is not affected by the presence of the other. If at any time the meter on one feeder is dead, the other meter is unaffected and no voltage selector relay is required. It is not usual to adopt this method for more than two circuits owing to the space which would be occupied by the meter elements. Each polyphase meter in the illustration has two single-phase elements for metering a three-phase three-wire supply but obviously two three-phase four-wire meters, each having three single-phase elements could be utilized in a similar manner.

11.5. Summation Meter with Paralleled Current Transformers. The simplest form of summation metering using only a meter and current transformers of standard construction, consists in paralleling the secondaries of current transformers in the circuits to be summated and passing the resultant current through the current coil of the summation meter. A connection diagram for such an arrangement is given in Fig. 167 which shows two circuits being summated on one meter. The circuits represented are two three-phase three-wire feeders each having a current transformer in the red and blue phases respectively. The secondaries of the two red current transformers are connected in parallel and the resultant current is passed through the red current

coil of the summation meter. The same procedure is carried out in the blue phase. For simplicity the voltage coils of the meter are shown connected to No. 1 feeder, but a voltage-selector relay is necessary and would be connected as shown in Fig. 164. The two circuits must of course, be of the same voltage and frequency and in synchronism.

This method is not limited to two circuits and can be extended to three, four or even more circuits; a slight inaccuracy results from this

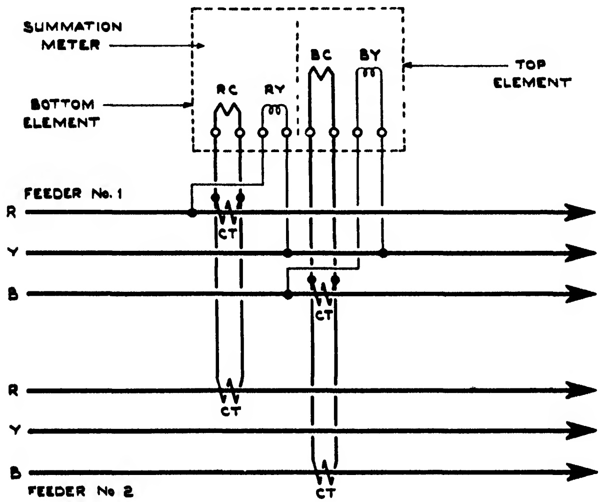


FIG. 167.—Connection diagram for summation meter having paralleled current transformers.

RC. Current coil in red phase.
BC. Current coil in blue phase.
RY. Voltage coil between red and yellow phases.
BY. Voltage coil between blue and yellow phases.
CT. Current transformer.

connection, the magnitude of which increases with the number of circuits which are paralleled. A normal allowance for this inaccuracy is 0·5 per cent. for each circuit in excess of one. Thus, if four circuits are connected in parallel, the normal limits of error for the meter would be increased by three times 0·5 per cent. or 1·5 per cent. increase. The error arises from the fact that if one or more of the feeders are dead, a small proportion of the secondary current from the transformers on the live feeders will flow in the reverse direction through the secondary of the dead transformer. This will be evident from Fig.

168 in which feeders Nos. 1, 2 and 3 are alive and carrying current, while feeder No. 4 is dead. The voltage across the secondary leads connected to CT4 will cause a small current to flow in the direction of the arrow. Owing to the impedance of the secondary winding, the current which is shunted from the meter current coil will be small and the allowance referred to above should be sufficient to cover the discrepancy under normal conditions.

A similar effect, but less in magnitude, will be noted if the load on the feeders is unequally distributed, resulting in corresponding inequalities in the transformer secondary currents; the magnitude of the error will depend upon the method of paralleling the current transformer secondaries. If the secondaries are connected as shown in Fig. 169 (*a*) and the total current is conveyed to the meter current coil through one pair of leads, the voltage across a dead secondary will be greater than if connected as in Fig. 169 (*b*) where each secondary delivers its current through an independent pair of leads direct to the terminals of the meter current coil. In the latter case the maximum voltage which can be applied to a dead secondary is the voltage drop across the meter current coil, whereas in the former this voltage will be increased by the voltage drop in the connecting leads. This drop may be relatively high if the distance separating the meter from the transformers is considerable. Other things being equal, the higher the voltage across the terminals of the dead transformer, the greater will be the current shunted from the meter current coil and the greater the error in the meter registration.

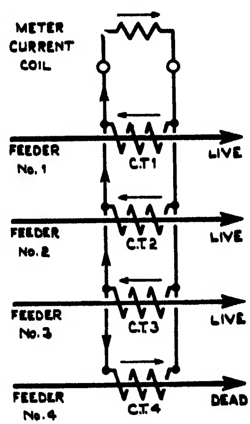


FIG. 168.—Summating four feeders with paralleled current transformers.

The current coil of the meter must be rated according to the maximum current which it may be expected to carry. If connected to four five-ampere secondary coils each of which may carry full load simultaneously, then a 20-ampere current coil would be desirable. In practice however, it is unlikely that full load will occur on each circuit simultaneously and consequently the meter would never carry full rated load. In order that good performance on low loads may be achieved, it is desirable to fit the lowest rated current coil consistent with capacity

to carry the maximum load. It will usually be found that a current coil rated at the equivalent of 75 per cent. or thereabouts, of the total full-load secondary current will suffice, which in this example would be 15 amperes. The current transformers connected to the meter current coil must all have the same transformer ratio, but they need not be similarly rated. Thus, two transformers in parallel could have ratios of 500/5 amperes which is equal to a ratio of 100/1. But if one of the circuits was intended for a lighter load than the other and the load did not exceed 300 amperes, then the corresponding transformer should have a ratio of 300/3 amperes, which is also equal to a ratio of 100/1.

Where several circuits are summated on a single meter, it is not always essential to fit voltage selector relays to select from every circuit

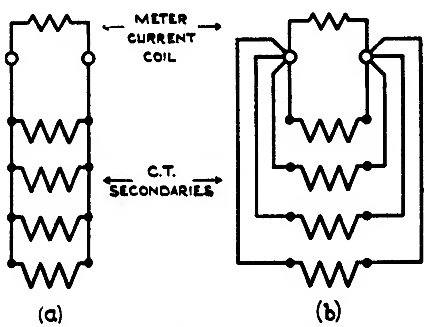


FIG. 169.—Alternative arrangements of paralleled transformer secondaries.

if a sufficient number is taken to ensure that one of the possible selections is always alive. Thus, if four feeders are being summated it may suffice to fit relays to select voltage from three of these. The risk which is incurred by this procedure is, that if three circuits are dead and the only live circuit is the one from which no voltage selection is available, there will be no registration on the meter during this period. If independent readings of kWh consumption are available and the sole object of the summation meter is the measurement of maximum demand the risk is negligible since the maximum demand is not likely to occur when three feeders are dead.

11.6. Summation Meters with Summation Current Transformers. The method of summation utilizing paralleled current transformers is convenient when the distances separating the meter and transformers are short, but it has disadvantages if the distances are considerable.

If, in order to obtain the best possible accuracy, the transformer secondaries are paralleled at the meter terminals as shown in Fig. 169 (*b*), a comparatively large number of conductors must be run a long distance involving considerable expense. If on the other hand, the transformer secondaries are paralleled at the source and a single pair of leads per phase are run to the meter, these must be of substantial section because they carry the sum of the secondary currents and again are likely to be expensive. In order to overcome these disadvantages, summation transformers* may be employed, one being required for each element of the summation meter.

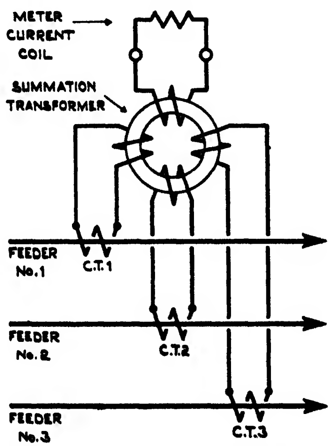


FIG. 170.—Summation by means of summation transformer.

A summation transformer has a number of primary windings corresponding to the number of circuits to be summated and one secondary winding, and each is proportioned to carry five amperes. A summation transformer for three circuits is shown in Fig 170. This method has the advantage that the primary transformers which feed the summation transformer need not have identical ratios. Thus, in Fig. 170 the current transformers in circuits Nos. 1, 2 and 3 might have ratios of 300/5, 400/5 and 500/5 amperes respectively. In such a case the summation transformer primaries would have a proportionate number of turns on each and the ratio would be expressed as 300 + 400 + 500/5 amperes. The summation transformer is preferably

* See also page 416 Summation Transformers.

arranged near to the primary transformers in order to reduce to a minimum the length of the connecting leads. Since the summation transformer errors are added to those of the primary transformers, the overall accuracy is somewhat less than that obtainable with paralleled transformers. On the other hand the number of circuits which can be conveniently summated is greater than by any of the methods already described. If, in a particular instance, summation transformers are used because of the distance separating the summation meter and the primary transformers, consideration may be given to the desirability of providing 1-ampere or 0·5-ampere secondaries on the summation transformers. The volt-ampere losses in the connecting leads vary as the square of the secondary current and for a given permissible loss in the leads, the distance separating the meter and transformers can be increased twenty-five times if a 1-ampere secondary is adopted or one hundred times for a 0·5-ampere secondary. Conversely, for a given distance, the losses in the leads can be reduced to one twenty-fifth or one-hundredth respectively for 1-ampere or 0·5-ampere secondaries. In this connection it is necessary to bear in mind the risks associated with the use of secondary currents of a low order as referred to in Section 12.13.

11.7. Summation by Electrical Impulses. All the foregoing methods of summation suffer from limitations which in many cases restrict their sphere of usefulness; the number of circuits which can be summated is comparatively small, the distances separating the points where the measurement and recording is made are usually limited and the accuracy of measurement becomes lower as the number of circuits increases. Further, they are not always adaptable to some of the complex conditions which arise in practice, where subtraction of quantities as well as addition must be provided for before the maximum demand of an installation can be determined.

Since the control of large-scale generation of electrical energy and its distribution over Great Britain through the high tension transmission lines of the British Electricity Authority was undertaken in 1932, summation metering has become of considerable importance. The sale of large quantities of electrical energy, the interchange of power between one area and another, the accurate determination of maximum demand, the recording of the variations in load throughout the day and the determination of the power-factor at the time of maximum demand have necessitated metering of a very high order of accuracy.

The methods of summation metering already described have been used to a limited extent and in suitable circumstances, but generally speaking they have not been sufficiently accurate to meet the requirements of large-scale generation and bulk supply in this country. Instead, precision meters have been developed which have been fitted

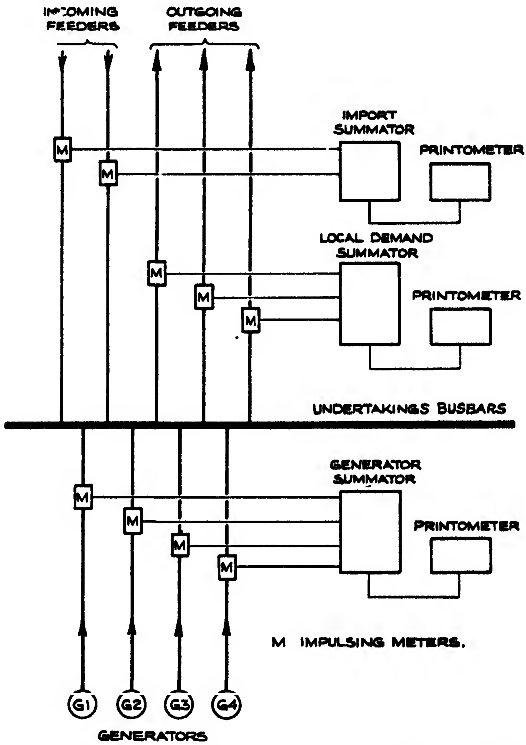


FIG. 171.—Impulse summation of positive quantities.

with contact-making devices sending electrical impulses to a summator. This instrument, actuated by the impulses received, records on separate registers the energy which has passed through each circuit connected to the summator the total energy passed through all the circuits, the simultaneous maximum demand on all the circuits and, if desired, passes on to another instrument impulses which are capable of producing a printed record of the demand every half-hour. This latter instrument, which may be a printometer or a chart recorder, provides

information which permits the load curve to be plotted throughout the day, week and month and is a check on the readings of the demand indicator.

A simple summation scheme is shown in Fig. 171 which indicates the arrangements made in a supply undertaking where four generators feed on to the undertaking's busbars and a supply is also obtained from a main transmission system. Three summators are provided, the first of which shows the amount imported from the main transmission system, the second the amount generated and the third the amount passed into the local distribution system. Each summator is fitted with a maximum-demand indicator and with a contact-making device which re-impulses on to a printometer giving a half-hourly record of the demand. For simplicity, a single-line diagram is used, the arrows showing the direction of power flow in the incoming and outgoing feeders and generator circuits. Each circuit has one meter fitted with impulsing contacts, the impulsing circuits being indicated by a single thin line connecting the meter to the summator. The local demand summator will register the sum of the kWh imported and generated, but the maximum demand shown will not be the sum of the maximum demands shown on the import and generator summators, since these will not necessarily occur at the same time.

A more complicated scheme involving the subtraction as well as the addition of quantities, is shown in Fig. 172. This indicates the arrangements made for summating the supplies in an undertaking having its own generating plant, with provision for importing from or exporting to the main transmission system and for exporting only to a distant undertaking or substation. Three summators are shown, each fitted with a maximum-demand indicator and capable of dealing with positive and negative quantities. In this connection, positive quantities are understood as being those which are added together in the maximum-demand indication and negative quantities as those which require to be subtracted.

The functions of the summators are as follows: the import summator registers the nett amount imported from the main transmission system. Two feeders, *A* and *B*, connect the undertaking's busbars to the main transmission system and these are arranged for power flow to take place in either direction, it being assumed that the direction will be the same in each at any given instant. The import meters are arranged to run in the forward direction when current is being imported. Ratchets and pawls are fitted to prevent reverse rotation when

energy is being exported. The export meters on these feeders are arranged to run in the forward direction when energy is being exported and likewise are fitted with ratchets and pawls to prevent reverse rotation.

Two additional feeders, *C* and *D*, connect the undertaking's busbars to a substation or distribution point, the maximum demand of which is measured at the distant end. If the energy imported through *A*

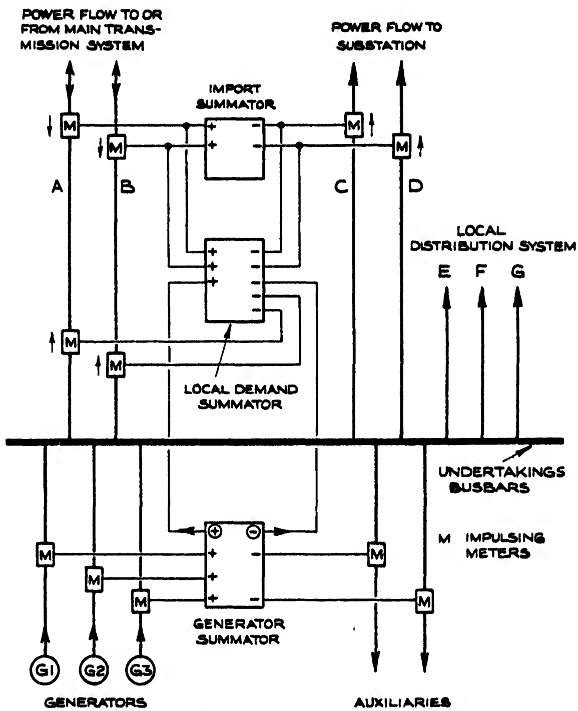


FIG. 172.—Impulse summation of positive and negative quantities.

and *B* is exactly equal to that exported through *C* and *D*, the number of negative impulses received by the import summator will be equal to the number of positive impulses and the two will cancel out. In these circumstances there will be no reading on the maximum demand indicator although the impulses received on each circuit will be registered. If the energy imported through *A* and *B* exceeds that exported through *C* and *D*, it is obvious that the balance is being absorbed in the local undertaking and the difference between these quantities will

be the nett import to the undertaking; this being a positive quantity will be duly recorded. If export is taking place over feeders *A* and *B* as well as *C* and *D*, the import meters will cease to register since the power flow has reversed and the ratchets and pawls will prevent backward rotation. All the impulses received on the import summator will be negative in sign and the summator is provided with a free-wheel or equivalent device to permit any excess of negative impulses to be bypassed without affecting the demand indicator.

Where it is necessary to provide for subtraction on a summator, it should be explained that this is not accomplished by reducing a total already recorded. Obviously this cannot be performed on a maximum-demand indicator and, in fact, most of the registering devices on a summator are fitted with a ratchet and pawl which permits forward movement only. Instead, subtraction is in effect accomplished by cancellation of positive impulses. Thus, if a negative impulse is sent to a summator, following the reception of a number of positives, the positive total is not reduced but the negative impulse is held in storage and is cancelled by the succeeding positive which is not recorded in the total. For example, assuming that in a particular time interval, 96 positive impulses have been received, followed by one negative and then two more positives, the reading on the totalizing register after receipt of each of the last four impulses would be 96, 96, 96, 97. The method whereby this is achieved varies in different makes of summator and will be explained later.

The generator summator in Fig. 172 registers the nett amount generated, after deducting the energy required for operating the power station auxiliaries. The two meters shown in the diagram, connected in circuit with the auxiliaries, impulse negatively on to the summator and cancel a corresponding number of positive impulses; the maximum demand indicator is actuated by the difference between the positive and negative impulses received. In the event of the generators being shut down the power for the operation of the auxiliaries would be derived from the import circuit and the generator summator would receive negative impulses only. In the absence of positive impulses a free-wheel device would permit negative impulses to pass through without having any influence on the demand indicator. This summator is shown with two contact-making devices which send impulses to the local-demand summator. One of these impulsing circuits re-transmits all the positive impulses received and the other re-transmits the negative impulses.

The local-demand summator in Fig. 172 registers the impulses received from all the various circuits and gives an indication of the maximum demand on the local distribution system which is supplied through the feeders *E F G*. The number of positive impulses received by this summator will always exceed the number of negative impulses and consequently no free-wheel device is necessary. The local demand is the sum of the amount imported, plus the amount generated, minus the amount exported, minus the amount used by the auxiliaries. If export is taking place over the feeders *A* and *B* the export meters on these feeders will be operative and the import meters will be stationary. In this case the local demand summator will be receiving negative impulses over five circuits, namely, feeders *A*, *B*, *C*, *D* and also from the generator summator. Positive impulses will be received over one circuit only, this being the positive impulsing circuit from the generator summator.

Since impulses do not come in at a regular rate it is possible that several negative impulses may come in succession without any positives. Should this condition arise during the interval in which the maximum demand is registered, an error would occur in the maximum-demand indication if any of these negatives were by-passed. Accordingly, provision must be made for the temporary storage of negative impulses received in succession in excess of one and for the release of the stored impulses immediately positives come along to cancel them. The method of accomplishing this function varies with different manufacturers and will be referred to in the descriptions which follow.

Referring to Fig. 172 it will be noted that impulses received on the local-demand summator from the generator and auxiliary circuits have been re-impulsed by the generator summator, whereas the import meters on feeders *A* and *B*, also export meters on *C* and *D*, each impulse on two circuits in parallel. Usually it is possible to adopt either of these methods as desired and the re-impulsing method is preferable where a large number of circuits are involved, since all the positive impulses received on a summator from a number of circuits can be re-impulsed on one circuit and all the negative impulses on another.

The number of circuits summated on a single instrument by impulsing methods, is usually limited to twelve or sixteen, but there is no practical limit to the number if re-impulsing is adopted. The accuracy which can be obtained is very high and there is no difficulty in transmitting impulses with a loss or gain not exceeding one per thousand, that is, with an error in transmission not exceeding 0·1 per cent. Further,

the greater the number of circuits summated, the closer will the average error approach zero, owing to diversity in the error of the impulsing meters. The distances separating the meters and the summator may be considerable as the current in the impulsing circuits is very small. No printometers or chart recorders are shown in Fig 172, but these can be added if re-impulsing contacts are fitted on the summators as indicated in Fig. 171 and on the generator summator in Fig. 172.

By connecting reactive meters in series with the kWh meters and duplicating the summators, it is possible to determine the variation in power-factor throughout the day as well as the variation in the load and to determine the power-factor at the time of maximum demand. This is a necessary condition in some tariffs where very large quantities of energy are bought or sold. Summation by means of impulsing methods enables the most complicated metering problems to be solved in a comparatively simple manner and is flexible and adaptable to a variety of circumstances. Several manufacturers in this country have developed summation metering schemes which have been adopted extensively and a description of the most important of these follows.

11.8. Landis and Gyr Summation Metering System. In the summation metering system adopted by Landis and Gyr, Ltd., the meters which initiate the impulses for actuating the summator are fitted with a contacting device driven by the meter rotor. The summator has a number of relays, one of which is associated with each impulsing meter. After the passage of a predetermined quantity of energy through a meter the impulsing contacts close momentarily and complete a circuit through a relay, the armature of which is tripped. The restoration of the relay armature to its normal position is accomplished by a camshaft driven by a small induction motor which runs continuously; the return of the armature to its initial position drives forward the registering mechanism of the summator by an amount corresponding to the value in kWh of the impulse received. Impulses may be received by the relays in rapid succession or even simultaneously, but the restoration of the armatures takes place in succession at definite time intervals, so that each armature makes its proper contribution to the total amount registered.

The contact-making device fitted to a Landis and Gyr impulsing meter is illustrated in Fig. 173. It consists of a pair of normally-open contacts, one of which is fixed and the other movable about a pivot-point. A light tension spring tends to bring the contacts together, but closure is prevented by a cam mounted on an arbor and secured to a weighted disc; the disc is freely mounted on a shaft which is co-axial with

another shaft driven by the meter and carrying a driving-pin. Normally the weighted side of the disc tends to remain in the position shown in Fig. 173 (*a*), but when the driving-pin, moving in a clockwise direction, engages with the weight, the latter is carried around until it reaches a position diametrically opposite; a slight further movement in a clockwise direction causes the weight to topple over and fall again to the bottom. During the movement of the weight from top to bottom, it passes through the position shown in Fig. 173 (*b*). At this position a flat on the cam allows the pivoted contact lever to move into the closed position, but the closure is only momentary as the weight, having gained some momentum, continues to travel until it again reaches the position shown in Fig. 173 (*a*). The driving-pin however, is still in the position

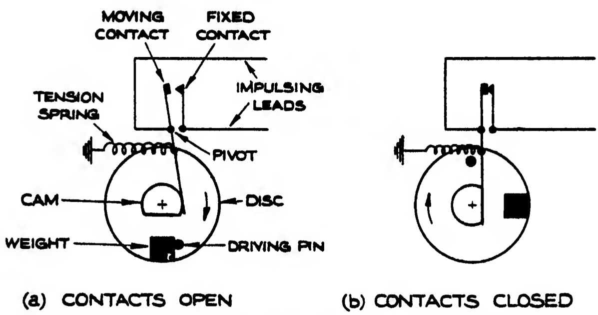


FIG. 173.—Contact-making device on Landis & Gyr impulsing meter.

shown in Fig. 173 (*b*) and will continue to be moved by the meter without encountering any opposition for a further half-revolution of the disc.

The power required to lift the weight from the lower to the upper position is supplied by the meter and as the load is not constant this effort influences the accuracy of the meter if operating on a low load. In order to reduce as far as possible the frictional load on the meter, the bearings of the contact-making device are jewelled. The magnitude of the error caused by the contactor will vary according to the number of revolutions of the rotor per impulse as naturally a rapid rate of impulsing will increase the amount of work the meter has to perform. The makers claim that in the case of a meter having a torque of approximately 8·5 cm-g. at full load, the maximum error due to the operation of the contact-making device will not exceed 1·5 per cent. at 5 per cent. load

when one contact is made for every 7·5 revolutions of the rotor; a slower rate of impulsing will result in a reduced error. The duration of contact is of the order of 0·07 second. If a single-phase meter is required to operate a contact-making device it is usual to employ a two-element meter in order to obtain a sufficient margin of torque.

A summator having eight elements is shown in Fig. 174 and a

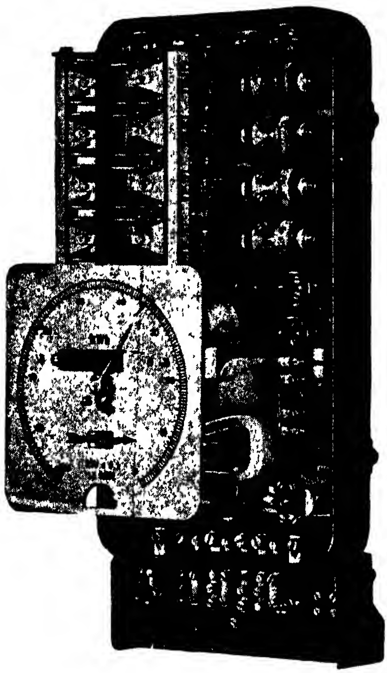


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FIG. 174.—Landis & Gyr eight-element summator.

diagrammatic view of the mechanism of a four-element summator in Fig. 175. In this diagram, three meters (11) are shown connected to three of the relays in the summator, the fourth relay being a spare. Two pilot wires connect each contact-making device to its corresponding relay, but if desired one wire will suffice together with one common to all the circuits. When a relay coil is energized its armature is attracted and a pivoted lever (1) is released; a spring (6) pulls the lower end of the lever against a stop and a pawl (9) slips over a tooth on the ratchet wheel (5). A shaded-pole motor (8) drives a cam-shaft (3) carrying four

cams (2) which are staggered 90 deg. apart so that each can engage in succession with a pin on one of the levers (1). Rotation of the cam-shaft

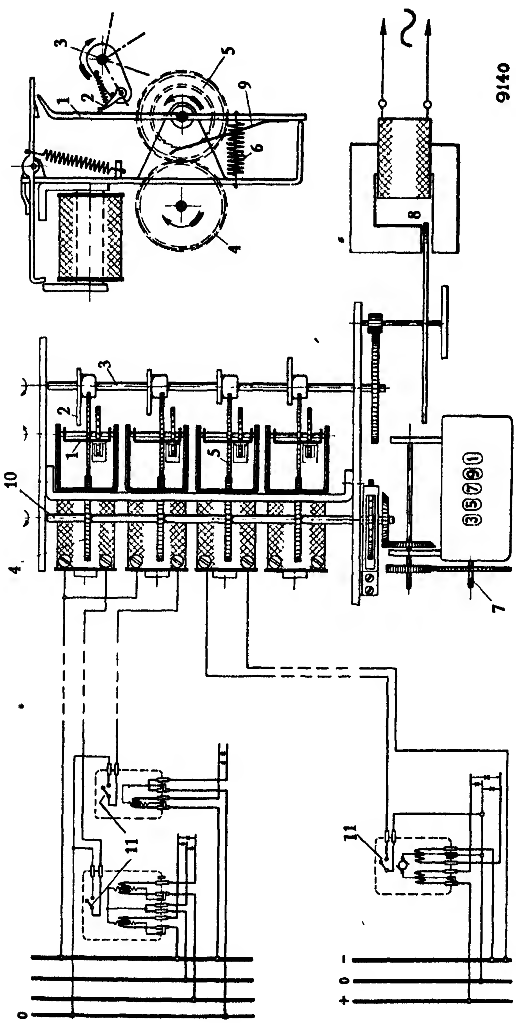


FIG. 175.—Diagrammatic view of Landis & Gyr four-element summator.

(3) causes the cam (2) to restore the lever (1) to its initial position where it is locked by a detent on the armature of the relay. The restoration of the lever (1) carries with it the pawl (9) which moves the wheel (5)

in an anti-clockwise direction, driving in turn one of the wheels (4) mounted on a common spindle (10). The latter is geared to the summation register (7) giving an indication of the total movement communicated by the four relays.

Each impulse communicated to the summator represents a definite value in kWh and advances the register by a corresponding amount. Accordingly, all the meters connected to a given summator must have equal impulse values. If the kW capacity of the meters differs the meters of the lower capacities will make a larger number of revolutions per impulse than the higher-capacity meters.

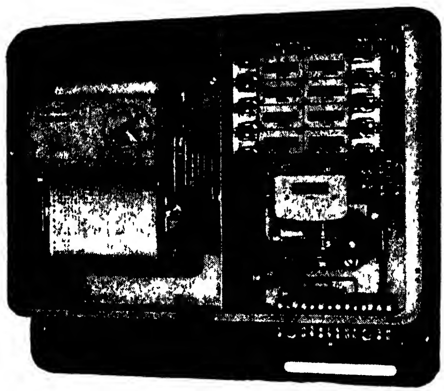


FIG. 176.—Landis & Gyr summator combined with demand recorder.

In conjunction with the summator, a demand recorder is used, known as a "Maxigraph". This consists of a chart recorder providing a graphic record of the variations in the average load on the summator during each integration period. An illustration of a Maxigraph attachment is given in Fig. 176. The attachment is mounted in the same case as the summator and is separated therefrom by a partition. A hinged cover gives access to the Maxigraph for the purpose of periodically changing the chart, but the partition prevents unauthorized interference at such times with the summator mechanism. The summator and recorder are mechanically coupled together by a shaft which passes through the partition.

The chart on which the record is made consists of a roll of specially prepared paper and no ink is required. The record itself consists of a

series of parallel straight lines, the lengths of which vary with the magnitude of the average load in a succession of equal time intervals. A silver marking wheel is moved across the chart by the summator, starting from zero at the commencement of each time interval. The wheel is clear of the chart when being moved by the summator, but is pressed on the paper at the end of each time interval and drawn to the zero position, leaving a clear impression which cannot smear. The appearance of a chart record is shown in Fig. 177. The effective width of the scale is 160 mm. (6·3 inches approx.)

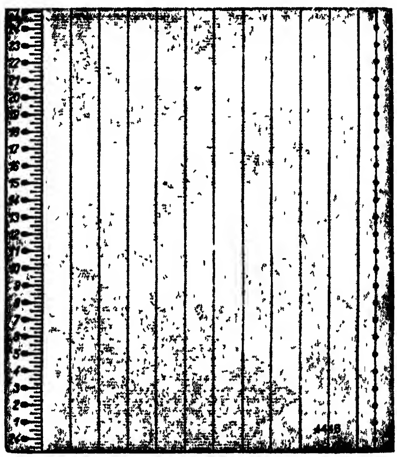


FIG. 177.—Chart for Landis & Gyr demand recorder.

11.9. Ferranti Summation Metering System. The Ferranti system of summation metering incorporates an integrating meter on each circuit, fitted with a contact-making device arranged for impulsing on to the summator. The latter is provided with an electromagnet associated with each contactor, the armature of the electromagnet being coupled through a ratchet and pawl device to a system of differential gears arranged to add together mechanically the impulses received by the electromagnets. Each electromagnet also actuates a register which duplicates the reading on the meter to which it is connected and the final shaft of the summating mechanism is coupled to a totalizing register and maximum-demand indicator. Where a printed record is required to show the variation in the demand throughout the day a

contactor is fitted in the summator which re-impulses on to a printometer. Thus, the coupling between the summator and printometer is electrical and the two instruments may be in separate cases, located, if need be, some distance apart.

The impulsing meter used by Ferranti Ltd. is of unusual design. It consists, in the case of the three-phase three-wire meter, of two elements and each element is provided with two voltage and two current coils. Thus, the meter has four voltage and four current coils and has in

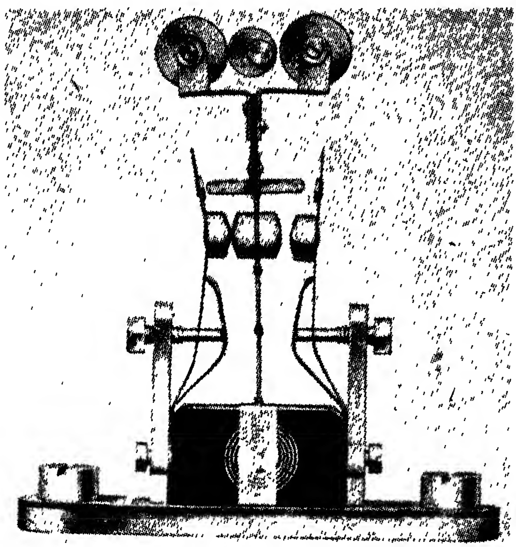


FIG. 178.—Ferranti impulsing contactor.

effect four driving elements. These are arranged so that the two driving elements in the red phase act on opposite diameters of one of the armature discs and the two driving elements in the blue phase act similarly on the other disc. In addition there are eight brake magnets arranged in pairs, two pairs acting on opposite diameters on one disc and two similar pairs on the other disc. The object of this arrangement is to obtain a balanced thrust on the rotor and to avoid any appreciable side-thrust in the bearings. The weight of the rotor is 81·5 grams which is somewhat high, but a magnetic suspension is provided which relieves the bottom bearing of approximately 70 per cent. of this weight.

A two-way impulsing contactor is driven by an auxiliary spindle

geared to the rotor-shaft. This contactor is illustrated in Fig. 178. The gearing between the auxiliary spindle and the rotor is arranged to suit the rate of impulsing desired. The contactor mechanism consists of a centre arm pivoted at one end, the other end being fitted with two brass rollers mounted in jewelled bearings to reduce friction, and two outer arms, each arm being fitted with heavy silver contacts. A cam fitted to the auxiliary spindle is located between the two brass rollers and as it rotates the cam engages each roller in turn, moving the centre

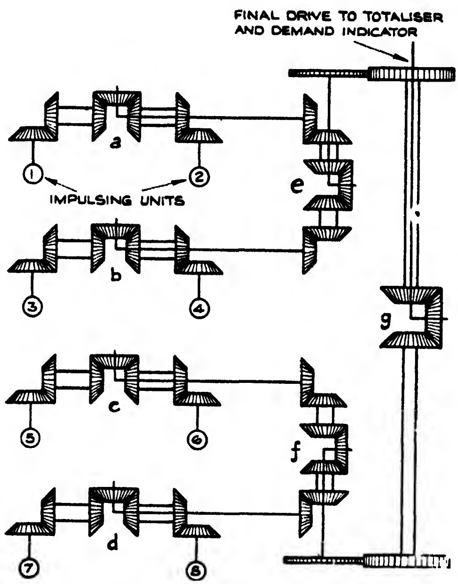


FIG. 179.—Arrangement of differential gears in Ferranti eight-element summator.

arm first to one side and then to the other. At each lateral movement contact is made between the centre arm and one of the outer arms. Adjacent to the contacts a small permanent bar-magnet is secured to the centre arm and the polar extremities of this magnet approach closely to a small iron rivet in each of the outer arms; the object of this magnet is to minimize the possibility of sparking at the contacts due to vibration at the time when the contacts are about to close or to open, by exerting a slight attraction between the magnet and the adjacent rivet. The summator to which the impulsing contacts are connected is fitted with a two-way inpulsing electromagnet for each impulsing meter and the

function of the meter is to cause the electromagnets to be energized alternately. Two resistors in the meter are connected in circuit with the impulsing coils to absorb the inductive discharge when the circuit is broken and to avoid sparking at the impulsing contacts.

The arrangement of the gearing in a Ferranti eight-element summator is shown diagrammatically in Fig. 179. It consists of a system of interconnected differential gears arranged as follows: Four differentials (a) (b) (c) and (d) are each driven by two impulsing electromagnets; differential (a) is driven by impulsing electromagnets (1) and (2) which turn the sun wheels in the same direction, so that the planet wheel is actuated by the sum of their separate movements. A register, also driven by each impulsing electromagnet, indicates in kWh the equivalent of the impulses received and duplicates the reading on the transmitting meter. Differential (b) is driven by impulsing electromagnets (3) and (4), the sum of their movements being communicated as before to the planet wheel. Similarly the planet wheels in differentials (c) and (d) receive the sum of the movements communicated by impulsing electromagnets (5) (6) and (7) (8) respectively. The sun wheels of differential (e) are driven in the same direction by movements communicated from the planet wheels in differentials (a) and (b) and consequently the planet wheel in (e) measures the sum of the movements initiated by impulsing electromagnets (1) (2) (3) and (4). The planet wheel in differential (f) in like manner measures the sum of the movements initiated by impulsing electromagnets (5) (6) (7) and (8). Finally the planet wheel in differential (g) measures the sum of the movements communicated by planet wheels in (e) and (f) and motion from this is communicated to a totalizing register and a demand indicator.

It will be obvious from the foregoing description that the principle involved in this method of summation is to summate circuits, first of all in pairs and then to summate the pairs, and so on. Any number of circuits can be dealt with in this manner, but the method becomes rather cumbersome when the number exceeds twelve. A little consideration will show that the number of differentials involved is one less than the number of circuits and in the example given eight circuits are summated by seven differentials.

If it is necessary to arrange for subtraction as well as addition, that is, to deal with negative quantities, this is effected quite simply by reversal of the drive to one of the sun wheels of a differential. Thus, if the registration of the meter connected to impulsing electromagnet

(8) in Fig. 170 is to be subtracted from the total, the sun wheel in differential (d) which is driven by impulsing electromagnet (8) must rotate in the reverse direction. The planet wheel in this differential will then measure the difference between the movements of its two sun wheels. Similarly, if the four circuits connected to impulsing electromagnets

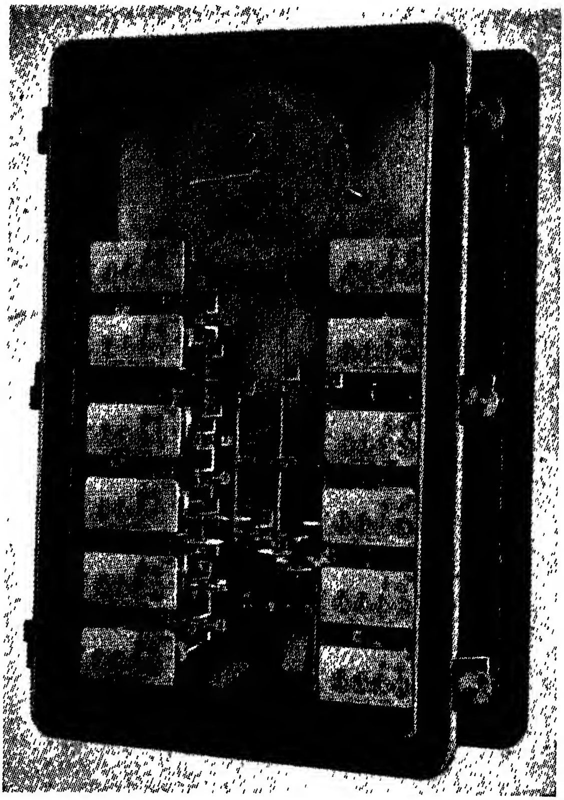


FIG. 180.—Ferranti twelve-element summator.

(5) (6) (7) and (8) are arranged for impulsing negatively, the sun wheel in differential (g) which registers the sum of their movements must be reversed in direction.

The general appearance of a Ferranti twelve-circuit summator is shown in Fig. 180. The demand indicator seen in the upper part of the instrument is of unusual construction in that it possesses two pointers,

one of which is capable of making ten revolutions; this permits the equivalent of a very long scale to be obtained in a small compass and small changes in demand may be easily distinguished. The maximum demand pointer is driven from the final shaft of the summator which also drives the totalizing register. This latter shows the total energy in kWh which has passed through the circuits connected to the summator. The demand pointer is coupled to the final shaft through a clutch which consists of two co-axial discs having cork-leather material on their opposing faces. At the end of an integration period (usually thirty minutes), a time switch energizes an electromagnet device which separates the opposing faces of the clutch and permits the driving mechanism of the demand indicator to return to a zero position under the influence of a spring; the demand pointers remain in position until they are moved forward again in some subsequent period of greater demand. At the end of an assessment period, which may be a month or a quarter, the demand pointers are reset to a low value or to zero, by hand, from outside the case. The act of resetting the pointers winds up a spring which provides the major portion of the energy required to drive the pointers and reduces to a low value the power required from the impulsing mechanism for this purpose.

When a summator is required to transmit impulses for the operation of a demand recorder or another summator a contactor similar to that used on impulsing meters is driven from the final shaft. The drive from the final shaft is through a spring coupling and a train of wheels, terminating in an aluminium brake-disc which rotates between the poles of a permanent magnet. The contactor is operated from the shaft carrying the aluminium brake-disc.

In a summator having a large number of impulsing circuits a series of impulses may come in rapid succession and from time to time two or more impulses may come simultaneously. The demand recorder or the succeeding summator cannot separate impulses which come through on one circuit simultaneously and the object of the spring coupling and brake-disc is to store in the transmitting summator, impulses which come in rapid succession and to release them at a rate which the following apparatus can deal with in a satisfactory manner. Any rotational movement of the final shaft of the transmitting summator imparts tension to the spring coupling, which in turn drives the brake-disc. Thus, impulses received by the summator in rapid succession leave the summator at a slower and more uniform rate.

The Ferranti demand recorder, or printometer as it is commonly

called, and which is used in conjunction with a summator, is an instrument which records on a roll chart, at predetermined intervals, the demand which has occurred in the circuits connected to the summator. The printometer is illustrated in Fig. 181. On the extreme right of the illustration may be seen an electromagnet having two coils which are energized alternately by impulses received from the summator. A pivoted armature located in front of the electromagnet is rocked back and forth as impulses are received and the reciprocating motion is

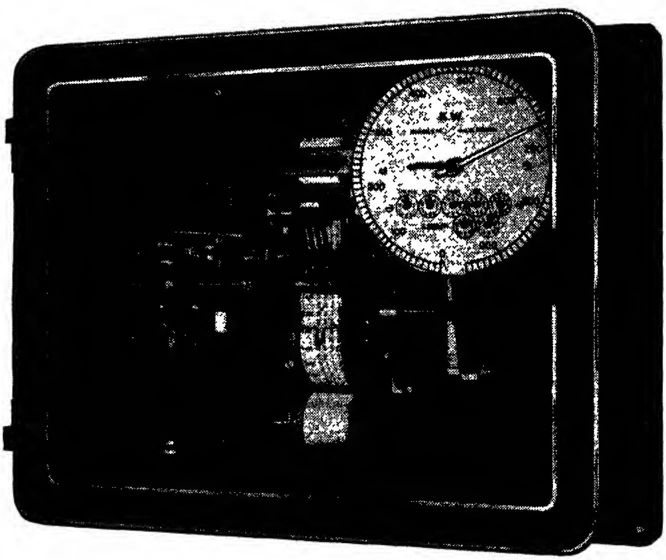


FIG. 181.—Ferranti printometer.

communicated to four figure-drums having raised figures (not visible in illustration), situated behind a paper strip. A register above the electromagnet is also advanced and the reading thereon serves as a check on the total number of impulses received.

The period over which the record is made is the same as for the demand indicator and is controlled by the same time-switch or clock used with the latter. At the end of the integration period the time-switch closes a circuit through an electromagnet seen in the top left-hand corner in Fig. 181, and an armature associated therewith is lifted, closing a pair of contacts. The following operations then take place:

1. The four figure-drums are locked in position and cannot be moved by further impulses received.
2. A motor, seen in the bottom left-hand corner in Fig. 181, is energized and, driving through a train of wheels, causes the figure-drums to print on a paper chart, through a carbon ribbon, the magnitude of the demand as shown on the drums.
3. After printing, the figure-drums are set to zero by the motor and are then ready to be actuated by impulses received in the next period.
4. On completion of the resetting, the drive from the impulsing electromagnets is restored. A spring storage device, which has received any impulses transmitted while the figure-drums were locked, discharges these impulses into the figure-drums.
5. The motor is switched off and impulsing continues until the end of the integration period when the cycle of operations is repeated.

A paper strip in the form of a roll of sufficient length to carry a month's records is carried on a drum in the top of the instrument. The strip passes behind a carbon ribbon and in front of the figure-drums previously referred to; it then passes over a sprocket and is wound on to a second roll in the bottom of the instrument. Four spring-actuated hammers are located in front of the paper strip and in alignment with the figure-drums.

The sequence of operations during a printing period is as follows:

1. The electromagnet energized through the time-switch releases a brake on the motor-shaft and the motor commences its run.
2. The transmission of impulses to the recording mechanism is transferred to the storage device.
3. Prongs are inserted in the figure-drums to align the figures.
4. The carbon ribbon is moved in front of the row of figures.
5. The hammers strike the carbon ribbon, making a printed record on the paper chart.
6. The prongs are removed and the figure-drums are reset to zero.
7. The stored impulses are released, advancing the figure-drums, and transmission is resumed.
8. The carbon ribbon is notched forward and lifted away from the figure-drums.

9. The chart is advanced ready for the next printing operation.
10. The motor is switched off and the brake applied.

It will be noted that no ink is used in this instrument. The carbon ribbon is carried on two spools and is gradually transferred from the one to the other. Sufficient ribbon is provided for three months' operation after which a new ribbon must be inserted. The paper chart carries the records for one month and is marked with the hour at which the record is made. The arrangement of the chart is such that several inches always remain visible and the demand figures for the previous twelve hours can be seen. The impulsing circuits in the printometer and summator are energized from a direct current source; if a local battery having a voltage of 50 volts or thereabouts is available, this may be utilized, failing which, a rectifier connected through a small transformer to an alternating-current supply may be provided.

11.10. Metropolitan-Vickers Summation Metering System. In the Metropolitan-Vickers summation metering system, impulsing meters fitted with contactors are connected through pilot wires to a summator, which adds together or subtracts, as the case may be, the impulses received from the impulsing meters. The summator is provided with a number of impulsing electromagnets coupled to a system of differential gears similar to the arrangement shown in Fig. 179 and to this extent operates on the principle adopted in the Ferranti Summator; the constructional details, however, are quite different. Each impulsing electromagnet actuates a register, a circuit-opening device and a ratchet and pawl drive to the differential system. The final shaft of the summator is coupled to a totalizing register and a demand indicator. Where a demand recorder is required this can be incorporated in the summator case and driven mechanically from the final shaft.

The impulsing meter used by Metropolitan-Vickers is not specially designed for summation metering, but is a modified form of the well-known Type N.E. polyphase meter fitted with a contactor unit. The contactor which is shown is Fig. 182 consists of a small commutator mounted in jewels and geared to the rotor-shaft. Three spring-supported brush contacts rest lightly on the commutator, the whole forming a simple single-pole two-way switch. The commutator and brushes are of a special alloy designed to operate with minimum friction and wear. It is claimed by the makers that the contacts are self-cleaning and that friction is not subject to cyclic variations over each revolution of the meter rotor. The gearing between the rotor and the commutator

can be varied to suit the rate of impulsing required. In this system, unlike most others, the value of each impulse transmitted by different meters connected to the same summator is not necessarily the same. Thus a 500-ampere meter, for example, may be geared to transmit 5 kWh impulses and a 100-ampere meter 1 kWh impulses.

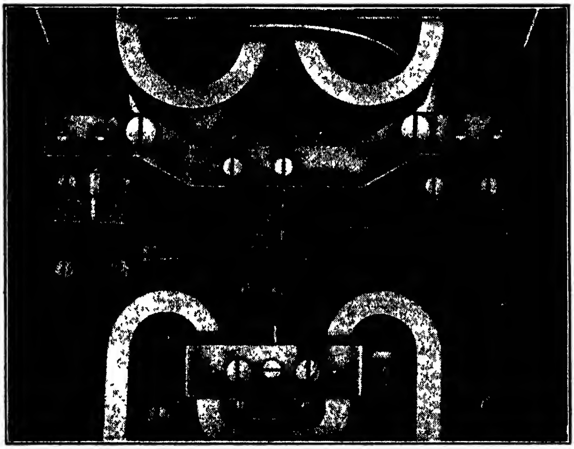


FIG. 182.—Metropolitan-Vickers impulsing contactor.

Three pilot wires connect the impulsing meter to the summator and a supply of current at a low voltage, 110 volts or less, is necessary for energizing the impulsing electromagnets. The connections between

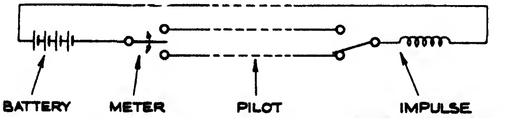


FIG. 183.—Impulsing circuit in Metropolitan-Vickers summation system.

each meter and the summator are shown in Fig. 183. The meter contactor is the equivalent of a single-pole two-way switch, the moving arm of which is moved slowly back and forth by the meter. The impulse-receiving element in the summator is also the equivalent of a single-pole two-way switch moved back and forth by an electromagnet; a direct-current supply obtained from a local battery or a rectifier

serves to energize the electromagnet. When a circuit is established at the meter contactor, the switch arm of the impulse-receiving element flies over from one contact to the other. The meter contactor makes

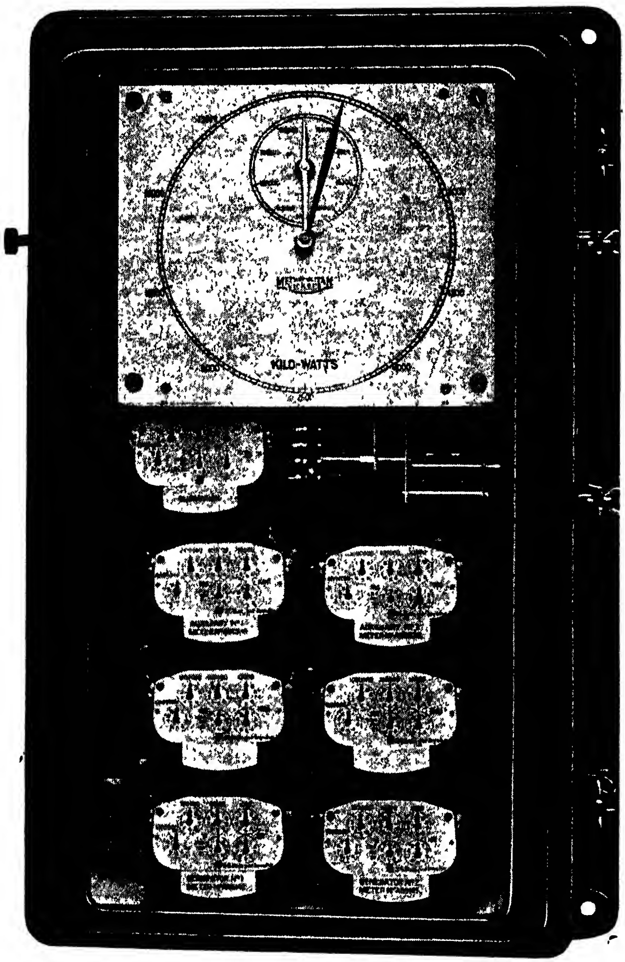


FIG. 184.—Metropolitan-Vickers six-element summator.

the circuit, but the impulse-receiving element breaks the circuit thus relieving the meter of a comparatively heavy duty and avoiding the possibility of damage to the commutator and brushes by sparking or burning.

An illustration of a Metropolitan-Vickers 6-element summator is shown in Fig 184. It consists of a glass-fronted case in the lower half of which six duplicating registers are fitted; these repeat the readings on the registers of the impulsing meters to which they are connected. A totalizing register which gives the sum of the readings on the duplicating registers is shown immediately above the latter and to the left. A maximum-demand indicator occupies the upper half of the case and immediately below on the right may be seen a demand recorder.

The impulse-receiving element together with the duplicating register and the two-way switch form a unit construction which can

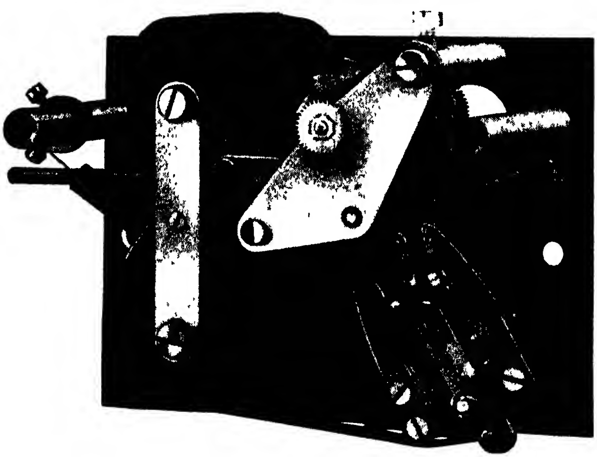


FIG. 185.—Metropolitan-Vickers impulse-receiving element.

be easily removed from the summator. An illustration of this element with the register removed is shown in Fig 185. It consists of an electromagnet having a pivoted armature which is coupled to a 10-tooth ratchet wheel. Each impulse received advances the ratchet wheel one tooth and this motion is communicated through suitable gearing to the register on the one hand and to the differential gear system on the other. Means are provided to prevent the ratchet wheel advancing by more than one tooth for each impulse as might otherwise occur in the event of excessive voltage. The two-way switch consisting of a pivoted arm provided with heavy-duty contacts moves between two fixed spring-blades having similar contacts. The arm is actuated by each movement of the armature and makes contact alternately with one fixed blade

and then the other. The totalizing register is mechanically operated from the final shaft of the differential gear system and not by an electromagnet.

The demand indicator has two pointers and scales as seen in Fig. 184; the large pointer can make up to ten revolutions, the actual number being indicated by the position of the small pointer. Thus, in effect, a scale equal in length to ten times the length of the longer scale is available and very close readings can be taken. The drive to the demand indicator is from the final shaft of the differential system

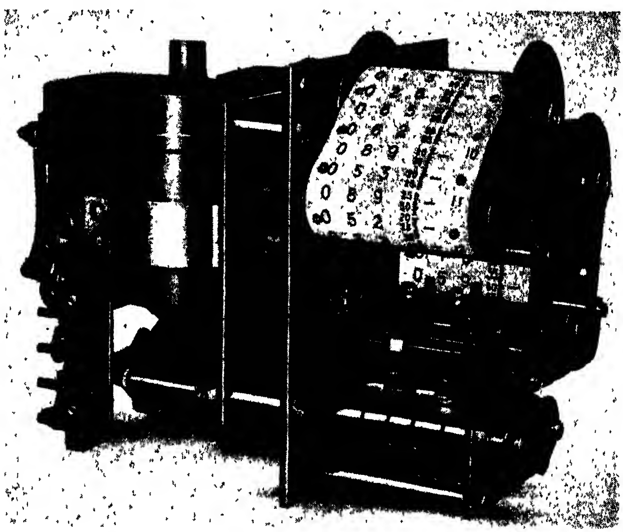


FIG. 186.—Metropolitan-Vickers printometer removed from case.

and is applied to one side of a secondary differential gear, the opposite side being held stationary by a clutch; the planet wheel of the differential is connected to the wheel train terminating in the demand pointer arbor. At the end of each demand period the clutch is released by means of a small electromagnet and a resetting weight causes the driving mechanism of the demand indicator to return to zero.

The printometer in the Metropolitan-Vickers summation system is usually built into the summator case and is much smaller and more compact than in other systems which have been described. It is directly driven from the final shaft of the summator and in the circumstances a separate totalizing register showing the equivalent of the impulses

received is superfluous since this is already provided as part of the summator. This, together with the omission of separate impulsing electromagnets, partly accounts for the reduced size of the demand

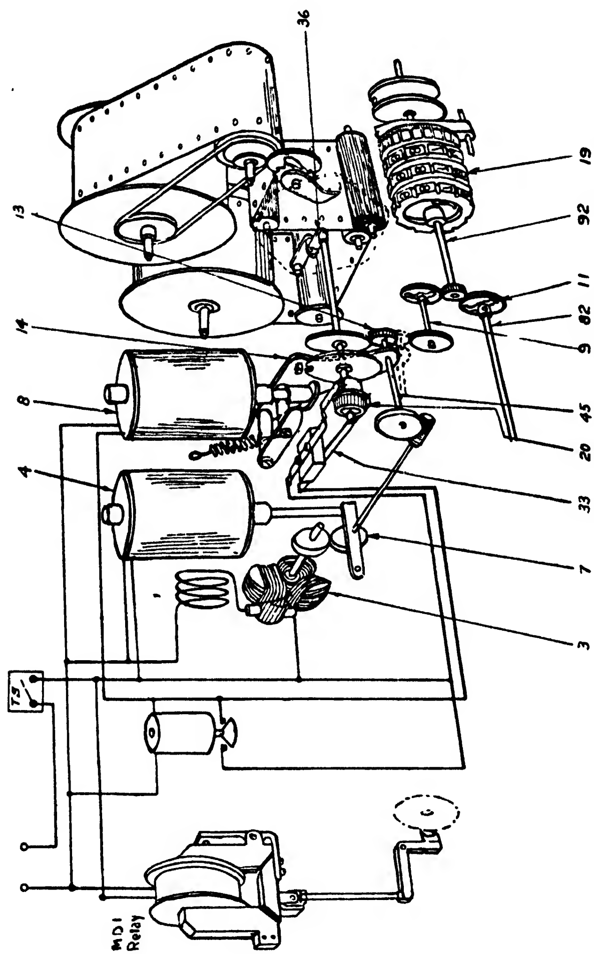


FIG. 187.—Diagrammatic arrangement of Metropolitan-Vickers printometer.

recorder. An illustration showing the printometer removed from its case is shown in Fig. 186 and a diagrammatic arrangement of the mechanism in Fig. 187. Access to the printometer for the purpose of removing or exchanging the chart is obtained through a small door on the side of the summator cover as seen in Fig. 184.

The operation of the printometer will be understood by reference to Fig 187. There are three type wheels of the cyclometer pattern, each bearing a single row of figures 0 to 9 around the periphery and a continuously-running fourth wheel with a double row of figures and a 100-division scale on the edge. These are driven from the final shaft of the summator and constitute the register. The paper roll chart on which the record is printed has the hours printed on one edge and is carried on a sliding carriage which also embodies a self-inking roller for inking the type wheels. The paper is punched with holes to register with locating-pins on the driving-drum. During each integration period, the register is driven forward concurrently with the demand indicator. At the end of the period an electromagnet disengages the type wheels from the final shaft of the summator and they become locked in position; at the same time a small motor is started and is geared to a mechanism which cranks forward the sliding carriage. An inking roller passes over the type wheels followed by the paper chart, which receives an impression of the figures against the appropriate hour mark. An arrow is printed against the scale on the vernier wheel to indicate the last two significant figures.

During the return movement of the carriage, the paper chart is automatically fed forward in readiness for the next record and the type wheels are unlocked. A second electromagnet then disconnects the motor drive from the carriage and connects it to the type wheels which are brought back to the zero position; the motor drive is then withdrawn from the type wheels and the drive from the final shaft of the summator is restored. The printed record just made can now be seen from the front of the summator.

The series of operations just described is initiated by a time-switch and occupies fourteen seconds; during this interval the impulses received by the summator are not registered either on the demand indicator or the demand recorder. Allowance is made for these lost impulses by assuming that the average rate of receiving impulses throughout the demand period is constant and by compensating the gear ratio between the final shaft and the two registers accordingly; thus a small excess registration takes place throughout the period of engagement to make up for the loss during disengagement. The makers claim that this assumption has been found to be justified in practice and that the totalizing register, the demand indicator and the demand recorder agree within plus or minus 0·1 per cent.

11.11. Chamberlain and Hookham Summation Metering System. The

summation metering system developed by Chamberlain and Hookham incorporates impulsing meters fitted with contact-making devices and associated with a summator having impulse-operated devices for summating and registering the impulses received. It differs from the systems

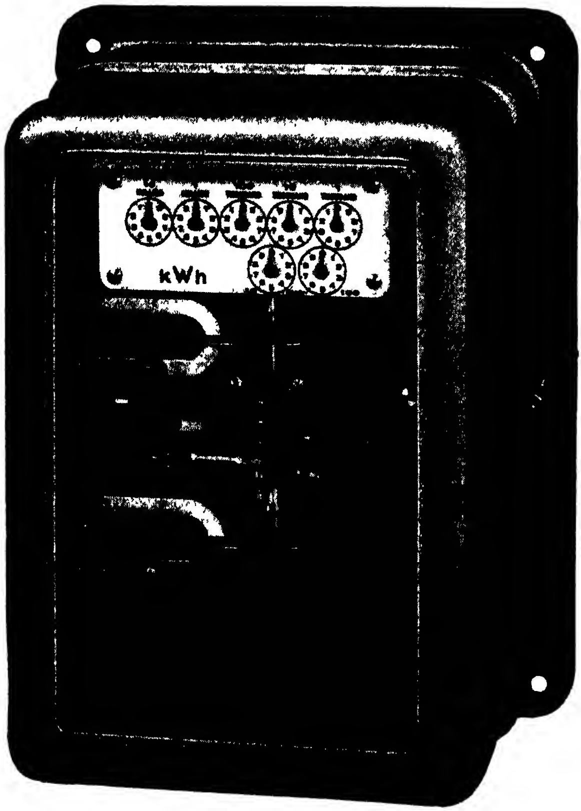


FIG. 188.—Chamberlain & Hookham impulsing meter. Type FN.

already described in that it relies on electrical means instead of mechanical, for achieving the desired results. In addition, the contactor on the impulsing meter receives electromagnetic assistance, independent of the measuring element, thus reducing the frictional load which is inseparable from all devices of this character, and prolonging the period during which the accuracy of the meter is maintained on low loads.

The impulsing meter normally supplied by Chamberlain and Hookham is the well-known Type FN polyphase meter as supplied for precision measurements, although a commercial grade meter may be used instead if desired. An illustration of the precision grade meter appears in Fig. 188, the contactor mechanism being visible between the two rotor discs. The arrangement of the contactor mechanism is shown in diagram form in Fig 189. The contactor is driven off a pinion mounted on the rotor shaft. The whole unit may be removed by the withdrawal of two screws and the disconnection of three wires, all easily accessible from the front. A wheel driven by the meter is mounted on a vertical spindle, together with a cross-arm having two downwardly projecting driving pins. A second vertical spindle carrying an

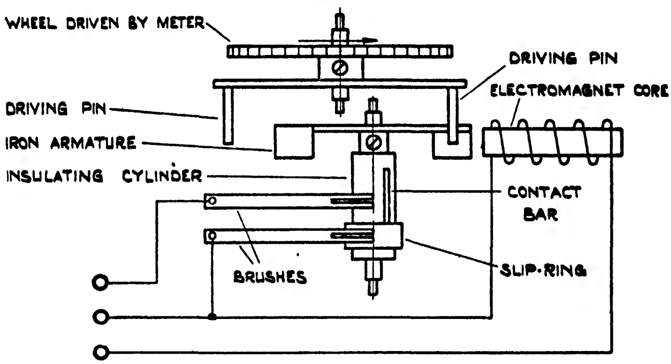


FIG. 189.—Chamberlain & Hookham impulsing contactor.

iron armature is located below the first and the axes of these spindles are slightly out of alignment. The second spindle also carries a cylinder of insulating material on which is mounted a silver slip-ring and two platinum contact bars spaced 180 deg. apart; the bars are in contact with the slip-ring and rest in grooves in the surface of the cylinder. The exposed surfaces of the contact bars are raised above the surface of the cylinder.

Two brushes are arranged so that one makes contact with the slip-ring as it rotates and the other makes contact with the bars in turn. The ends of the brushes are tipped with platinum and the upper brush is set so as to be clear of the surface of the insulating cylinder. Firm contact can however be established between this brush and the projecting portion of the contact bars. An electromagnet is disposed adjacent to

the iron armature in such a position that when the electromagnet is energized, the armature is suddenly attracted, causing it to pull the contact bar through the closed to the open circuit position. The end of the brush is shaped so that during this movement the contact bar lifts the brush, thus increasing the pressure between the contact surfaces and ensuring a reliable connection. At the same time the action is extremely rapid and a clean break is made when the circuit opens.

Owing to the two vertical spindles being out of alignment only one of the driving pins can engage with the armature at any time. Further, the period of engagement is very short because immediately a contact bar touches the brush, the armature is impelled forwards and away from the driving pin, and turns the insulating cylinder nearly half a revolution. The only work the meter is called upon to perform, is to rotate idly the first vertical spindle, and at intervals of short duration to move forward slightly the second vertical spindle. This is a very light duty which imposes a negligible load on the meter and is substantially constant. The power which is necessary for establishing a firm contact and for quickly breaking the circuit is supplied from an external source. Because of this, ample power is available and the disadvantage from which some other forms of contactor suffer is completely overcome. The rapidity with which the contactor moves gives the appearance of a flick and the device is appropriately called a "flick contactor".

An advantage possessed by the flick contactor is that it gives a visible indication that the impulsing circuit is healthy; this is particularly useful where a considerable distance separates the meter from the summator. If it should happen that a fault occurs in the impulsing circuit the electromagnet will not be energized periodically and the meter will then rotate the contactor. Any sluggishness in the flick action indicates that a fault may develop and steps can be taken to investigate the cause and rectify the same before any failure occurs. In order that the rate of impulsing may be varied to suit different sizes of meter, the gear ratio between the rotor and the first vertical spindle in Fig. 189 can be adjusted by means of an intermediate wheel and pinion (not shown in drawing).

An illustration of a Chamberlain and Hookham 6-element summator is given in Fig. 190. It consists of a case having a glass front and sides, giving a view of the apparatus behind the front plate. The six duplicating registers occupy the upper part of the summator and the maximum demand indicator the lower part. The demand indicator has a large-diameter scale and a single pointer. The scale length is

30 inches and can easily be read to less than $\frac{1}{32}$ inch or to 0·1 per cent. of the full-scale reading. The totalizing register is well separated from the duplicating registers and is enclosed within the demand-indicator scale. Removal of the cover of the summator gives access to two screws which, when withdrawn, permit the front plate to be swung

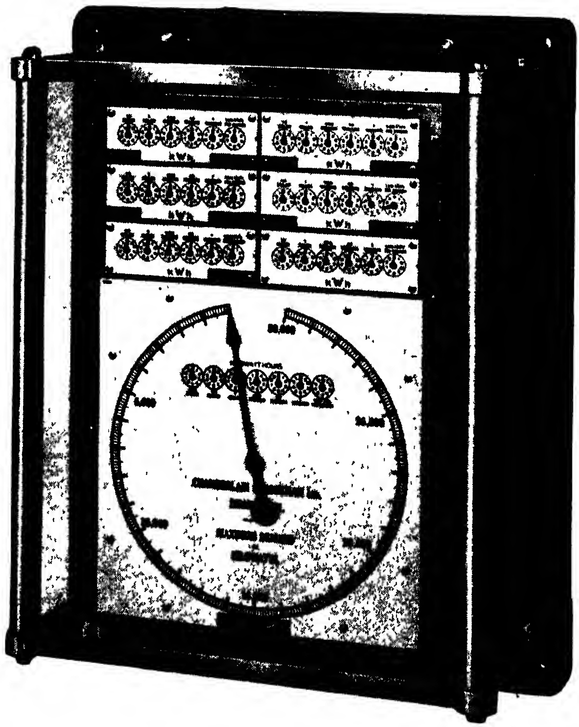


FIG. 190.—Chamberlain & Hookham six-element summator.

outwards on hinges, exposing the whole of the working parts for examination and cleaning.

The electrical circuits of a 3-element summator and its associated meter contactors are shown in Fig. 191. The meter contactors *MC*1, *MC*2, *MC*3, are connected through pilot wires to relays *R*1, *R*2, *R*3 in the summator. Each of the relays, which are of the type used in telephone practice, is fitted with two single-pole 2-way switches and normally the moving blade rests on the bottom contact as shown in the diagram. When current passes through a relay coil the two moving

blades are lifted simultaneously to the top contacts. When no current is passing, the contacts *A*1, *A*2, *A*3 are in series and connected to the positive pole of the supply, while the contacts *B*1, *B*2, *B*3 are also in series and connected to the negative pole of the supply.

The altered condition when one of the meter contactors *MC*1 is sending an impulse, is indicated in the diagram by the dotted lines. When the contacts at *MC*1 close, a circuit is completed from the positive terminal of the *DC* supply, through the contactor *MC*1 and the relay coil *R*1, over the bottom contacts at *B*2 and *B*3 to the negative terminal. This energizes relay *R*1 and the blades lift to the top contacts. A circuit is now completed by the relay from the positive terminal,

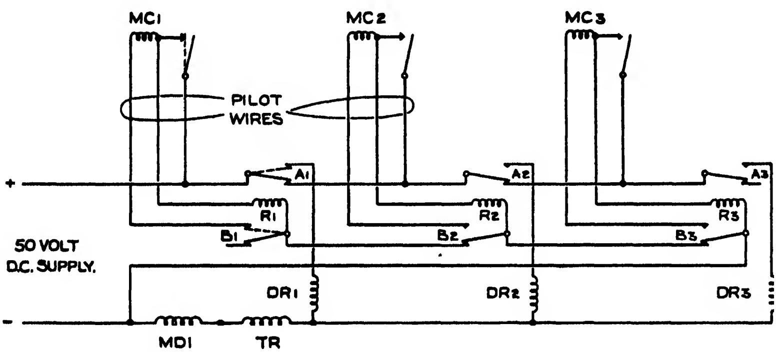


FIG. 191.—Arrangement of circuits in Chamberlain & Hookham three-element summator.

across the top contact at *A*1, through the coils of the duplicating register *DR*1, the totalizing register *TR* and the demand indicator *MDI* back to the negative terminal. This notches on each of these mechanisms one tooth. A second circuit is completed by the relay from the positive terminal, through the contacts and coil at *MC*1, across the top contact at *B*1 and the bottom contacts at *B*2, *B*3 back to the negative terminal of the supply. Immediately the coil at *MC*1 is energized, the contacts open, the circuit through *R*1 is broken and the blades at *A*1, *B*1 return to their normal position. It will be seen that the relay contacts at *A*1, *A*2, *A*3 are in the impulse-registering circuits of the summator and the contacts at *B*1, *B*2, *B*3 in the meter contactor clearing circuits.

The time taken to register an impulse and to restore the circuit to normal is less than 0·1 second. If, during this short time interval a

second meter contact closes, its associated relay cannot operate because the circuit is open. For example, if *MC*2 closes while *MC*1 is sending an impulse, *MC*2 is temporarily inoperative because the positive feed is broken at *A*1. Similarly, if *MC*1 closes while *MC*3 is sending an impulse, *MC*1 is inoperative because its negative return circuit is broken at *B*3. If six meters can be set so that all the contactors close simultaneously (a very unlikely contingency), all the impulses will register correctly and in succession. The time taken to complete the operation will not exceed one second.

The totalizing register *TR* and the demand indicator *MDI* are in series with each of the duplicating registers and consequently register

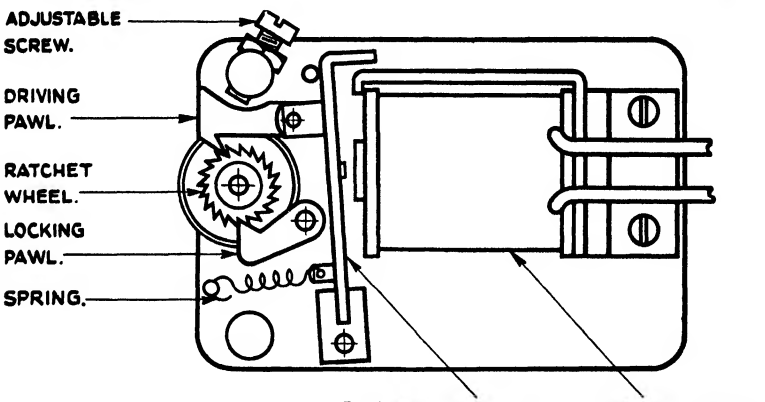


FIG. 192.—Chamberlain & Hoohkam impulsing electromagnet.

all impulses; the impulsing electromagnet fitted to each register and demand indicator is shown in Fig. 192. The electromagnet, when energized, attracts a pivoted armature to which a pawl is attached; the pawl engages with a 20-tooth ratchet wheel which is advanced one tooth on the return movement and a locking pawl prevents a reverse movement of the ratchet wheel. The arbor on which the ratchet wheel is mounted drives through suitable gearing on to the first pointer of the register or the demand indicator. The power for energizing the various electromagnets is obtained from a 50-volt direct-current supply. Where a number of summators are installed a small transformer and a rectifier are provided to feed the whole installation, but where one summator only is required the transformer and rectifier are accommodated inside the summator case.

Earlier in this chapter, reference has been made to the methods of dealing with negative impulses. Bearing in mind that the main object of summation metering is to arrive at the maximum demand, consideration must be given to the influence of negative impulsing on the indication of the summator. Take for example the generator summator *GS* in Fig. 172. Here three generators are impulsing positively and two auxiliary circuits are impulsing negatively. The maximum load supplied to the undertaking's busbars is the difference between the power generated and the power used by the auxiliaries in the station.

At the time of peak load, which is of course the time when the maximum demand will be registered, the power used by the auxiliaries will be a relatively small proportion of the total amount generated. If one assumes that the auxiliary plant absorbs five per cent. of the amount generated at the time of peak load, then one negative impulse will be received for every twenty positive impulses. On the other hand, if the station is acting as a stand-by and the generating plant is liable to be shut down during periods of light-load or at week-ends, there will be occasions when the generatior summator receives nothing but a succession of negative impulses, due to the power taken by the auxiliary plant. Obviously, when this condition arises, it cannot be at the time of maximum demand and no error will occur in the maximum demand registration if the negative impulses are by-passed. This would not be the case, however, when generation is taking place and some discrimination must be exercised as to when it is permissible to by-pass negative impulses.

The method adopted for dealing with negative quantities in the Chamberlain and Hookham summator will be understood by reference to Figs. 191 and 193. All the circuits of the summator which are impulsing positively are connected as shown in Fig. 191, but the coils of the demand indicator *MDI* and the totalizing register *TR* are omitted; the circuits impulsing negatively are dealt with in a similar manner. The coils of the relays *R*1, *R*2, in Fig. 193 are connected across the points in the circuit left open by the omission of the coils *MDI* and *TR* in Fig. 191. If now the summator is receiving positive impulses only, these will be duly registered on one or another of the duplicating registers *DR*1, *DR*2, *DR*3, passing through the relay coil *R*1 in Fig. 193 and back to the negative terminal of the *D.C.* supply. On the other hand, if the summator is receiving negative impulses only, these will be registered on another circuit and another set of duplicating registers. They will be passed on to the relay coil *R*2 in Fig. 193 and will return

to the negative terminal of the *D.C.* supply. The 50-volt *D.C.* supply shown in both diagrams is the same supply in each case.

Consideration may now be given to the circuit represented in Fig. 193. This consists of four relays *R*1, *R*2, *R*3, *R*4, each having a single-pole switch with normally-open contact which closes during the passage of an impulse through the relay coil. In addition there are two relays *R*5, *R*6, each having two single-pole 2-way switches with normally-closed bottom contact as shown in the diagram. The effect of a positive

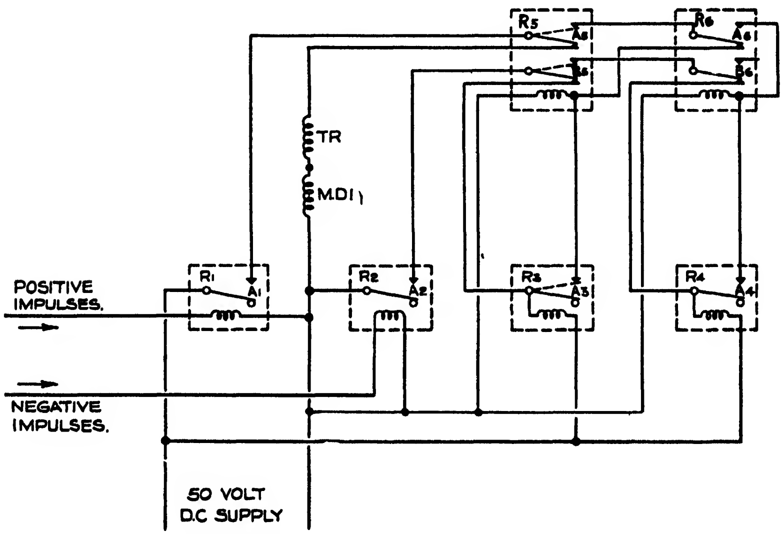


FIG. 193.—Circuit arrangement for negative impulsing in Chamberlain & Hookham summator.

impulse through the relay *R*1 is to close momentarily the contact *A*1, completing a circuit from the positive terminal of the *D.C.* supply across contact *A*1, across normally-closed bottom contact *A*5 of relay *R*5, through the totalizing register and demand indicator, and returning to the negative terminal of the *D.C.* supply. This process will continue so long as an uninterrupted series of positive impulses is received.

The effect of a negative impulse through the relay *R*2 is to close momentarily the contact *A*2. This completes a circuit from the positive terminal of the *D.C.* supply, through the coil of relay *R*3, across the normally-closed bottom contact *B*5 of relay *R*5, across the closed contact *A*2 of relay *R*2, returning to the negative terminal of the *D.C.*

supply. Immediately $R3$ is energized the contact $A3$ closes, connecting the coils of relays $R3$ and $R5$ in series across the *D.C.* supply and closing the top contacts at $A5$, $B5$. The position of the contacts in relays $R3$, $R5$ is now as shown by the dotted lines and both relays are locked in this position as the coils remain energized. The negative impulse has not effected any registration on the demand indicator or totalizing register and the contact $A2$ has re-opened.

If another negative impulse follows before a positive, contact $A2$ will close and relays $R4$, $R6$ will lock in, in the same manner as $R3$, $R5$, again with no effect on the demand indicator or totalizing register. This locking in of a pair of relays is equivalent to the storage of a negative impulse. Should it be necessary to store more than two impulses, this can be accomplished by the addition of two more relays similar to $R4$, $R6$, for each impulse to be stored, the connections being a repetition of those already shown.

Let it now be assumed that a positive impulse follows; this passes through the coil of relay $R1$, closing contact $A1$. A circuit is completed from the positive terminal of the *D.C.* supply across contact $A1$, across top contact of $A5$, across top contact of $A6$, across contact $A4$ (the latter three being locked in) and through the coil of relay $R4$ back to the positive terminal of the *D.C.* supply. Thus closure of $A1$ short-circuits the relay coil $R4$, resulting in the opening of contact $A4$ and the release of relay $R6$, but without any registration on *MDI* and *TR*. In a similar manner another positive impulse will unlock relays $R3$, $R5$. All the relays have now reverted to the condition shown in the diagram, with the contact blades in the bottom position and a continuation of positive impulses will cause a resumption of registration. It will be seen that after one or more negative impulses have been received in succession, an equal number of positives is required to cancel them, the net result being the same as if they had been subtracted from the total.

In order to avoid the necessity for storing a large number of negative impulses, it may be desirable to summate the negative circuits in a single meter by means of paralleled current transformers, multiple current windings or another of the methods described earlier in this chapter. This will not alter the actual number of negative impulses received since these would be the same whatever system of summation is adopted. The summating meter would be fitted with a contactor and all negative impulses would then pass over one impulsing circuit. This would ensure a more even distribution of impulses and would

prevent two or more negative impulses being received in rapid succession from time to time. By these means a single storage circuit would suffice where the magnitude of the load to be subtracted from the total is relatively small, as for example in the summation of generators and their auxiliaries.

Should the condition arise where the generators are shut down while the auxiliary plant is still in operation, as may occur in some generating stations at week-ends or at other times, a long succession of negative impulses will be received which are of no importance, so far as the measurement of maximum demand is concerned. In such a case these impulses may be by-passed and this will occur automatically as soon as the storage circuit or circuits can accept no more impulses. On referring to Fig. 193 it will be seen that negative impulses may continue to pass through the coil of relay *R*2 resulting in closure of contact *A*2. Nothing happens, however, since, with storage circuits full, there is no circuit beyond the dead-end contact at *B*6 in the relay *R*6, and the effect on the performance of the summator is the equivalent of a free-wheel device.

The maximum-demand indicator in the Chamberlain and Hookham summator is of conventional pattern and free from any complication. A train of wheels driven from the impulsing electromagnet terminates in a large wheel, co-axial with the arbor carrying the demand pointer. The pointer arbor is provided with a brake disc having a leather-lined brake shoe bearing on its periphery and a spring which tends to drive the pointer to a zero position; the large wheel carries a driving-pin which engages with a similar pin on the brake disc. A second spring tends to drive the large wheel to a zero position. Starting with the mechanism at zero, impulses passed through the impulsing electromagnet drive through the wheel train and advance the pointer in small steps. At the end of an integration period, an electromagnet, controlled by a clock or time-switch, is energized and the pinion which drives the large wheel is lifted out of engagement. The large wheel under the influence of its spring flies back to zero, but the pointer is retained in position by the friction brake.

The time taken to set the driving mechanism to zero is less than two seconds and consequently no compensation for lost impulses is necessary. It is a debatable point whether stored impulses belong to the period which has just expired or the period which has just commenced and by reducing the resetting time to a negligible amount the problem is avoided. In the next integration period the large wheel starting from

zero advances towards the position where it can again drive forward the brake disc, but engagement between the two does not take place unless and until a greater number of impulses pass through the impulsing electromagnet than were received in the previous integration period.

At the end of an assessment period, which may be one month or three months, the pointer will indicate the maximum demand which has occurred since it was last set to zero. An electromagnet is provided which, when energized, lifts the shoe off the brake disc and simultaneously disengages the pinion driving the large wheel; both pointer and large wheel then return to zero. A switch or press button, which can be sealed to prevent unauthorized use, is fitted at some convenient point external to the summator and is used to control the periodical reset of the pointer to zero. Where a number of summators are installed, all can be connected in parallel and set to zero simultaneously by the use of the switch.

The printometer used with the Chamberlain and Hookham summator is usually of the type illustrated in Fig. 181, page 389, although almost any type of impulse-operated demand-recorder can be used if desired. The impulsing contactor is fitted on the demand-indicator mechanism or the totalizing register and consists of a heavy-duty single-pole 2-way switch.

11.12. General Remarks Relating to Demand Measurement and Recording. The charges for the supply of electricity in bulk from the Grid to supply authorities are usually subject to agreement between the vendor and the purchaser. The agreement incorporates provisions relating to maximum demand in kW and the power-factor at the time of maximum demand. Similar agreements exist between the supply authority and the large power user and not infrequently the charge for the supply is based on the kWh consumed, with a fixed charge in addition, depending upon the maximum demand in kVA. It is generally accepted by the power consumer that a kVA demand charge is sound in principle; from the point of view of the supply authority, it is justified and is preferable to a kW demand charge.

It may be wondered why a kVA demand charge is acceptable when considering the supply of electricity to power users and is not acceptable when considering bulk distribution. There are two good reasons for this attitude. In the first place the British Electricity Authority who are the bulk distributors, insist upon the highest possible standard of accuracy in their metering installations. The measurement of kVA

demand cannot be accomplished with anything like the same degree of accuracy as the measurement of kW demand. In the second place, kVAh and kVA demands cannot be summated by methods which involve the arithmetical addition or subtraction of quantities as in impulse summation.

Many attempts have been made by meter designers and others to produce an accurate kVA meter and numerous types are available in varying degrees of complication and costliness. All, without exception, fall short of the accuracy with which kW demand can be determined. As regards summation of kVA, 100 kVA + 100 kVA does not equal 200 kVA if the power-factors of the two quantities differ. Vectorial summation by means of summation transformers or multiple current windings on meters can be accomplished but these methods are usually unsuitable for other reasons.

Because of these limitations in measurement, it is customary in dealing with large-scale generation and distribution to supply authorities, to charge for the maximum demand in kW and to vary the charge according to the power-factor at the time of maximum demand. This can be done by more precise methods than are available for the measurement of kVA. In order to determine the power-factor at the time of maximum kW demand, it is necessary to duplicate substantially the whole of the metering equipment necessary for the determination of kW demand.

The method of measurement is as follows: By means of the kWh meters and associated summators the maximum demand in kW is indicated. The time at which the maximum demand occurred can be ascertained by reference to the chart record on the demand recorder or printometer operated from the summator. By means of reactive meters and associated summators, the maximum demand in reactive kVA is indicated. Demand recorders or printometers operated from the reactive summators give a continuous chart record of the variation in the reactive demand. Knowing the time interval in which the maximum demand in kW occurred, one can refer to the same time interval on the reactive chart and ascertain therefrom the corresponding reactive demand. With this information available, the power-factor at the time of maximum kW demand can be calculated. The demand indicator on the reactive summator is not an essential part of this equipment since the maximum reactive kVA demand may not occur at the time of maximum kW demand. The correct value for the purpose of calculating the power-factor will be shown on the chart record, but the reactive demand indicator is useful as a check on the printometer.

In purchasing large amounts of electrical energy, the purchaser may feel justified in installing duplicate metering equipment in order to check the accuracy of the charges levied. Insofar as the maximum-demand charges are concerned, it is essential that the measuring periods shall coincide, otherwise discrepancies are likely to arise due to overlap in the timing. Charges for supplies from the Grid are based upon thirty-minute integration periods starting at each hour and half-hour thus: 1.0 p.m., 1.30 p.m., 2.0 p.m., 2.30 p.m. This system is also desirable on account of comparison with the chart records: it is also necessary for record purposes to refer to Greenwich Mean Time. Changes to Summer Time, Double Summer Time and back again may lead to confusion, particularly as the changes which take place do not usually occur at the end of a month or coincide with the changing of charts.

CHAPTER XII

CURRENT TRANSFORMERS

12.1. Why Current Transformers are Used. A current transformer is an instrument transformer for the transformation of current from one value to another, usually a lower one, or for the transformation of current at a high voltage into a proportionate current at a low voltage with respect to earth potential. Current transformers are used in conjunction with alternating-current meters or instruments where the current to be measured is of such magnitude that the meter or instrument current coil cannot conveniently be made of sufficient carrying capacity. They are also used wherever high-voltage current has to be metered, because of the difficulty of providing adequate insulation in the meter itself. In this connection supply voltages exceeding 660 volts are considered to be high voltage. In meter practice current transformers are used wherever the current to be metered exceeds 100 amperes, and in some instances a lower value than this is regarded as the desirable maximum for direct measurement.

12.2. Construction of Current Transformers. A current transformer comprises a magnetic circuit, usually in the form of iron stampings assembled together to form a core, on which are wound two electric circuits called the primary winding and secondary winding respectively. The primary winding carries the current to be measured and is connected in the main circuit. The secondary winding carries a current proportional to the current to be measured and the secondary terminals are connected to the current winding of the meter or instrument. Both windings are insulated from the core and from each other. The secondary insulation is arranged to withstand a test pressure of 2,000 volts applied between the winding and the core for one minute. The insulation on the primary is arranged to withstand for one minute a test pressure applied between the primary and secondary windings approximately equal to four times the voltage existing under working conditions. During this test the core and the secondary winding are connected together.

The primary circuit of a current transformer may consist of a single conductor in the form of a bar or cable instead of a winding, when the current to be measured is of the order of 600 amperes or

more. In low-voltage circuits the current to be measured may be so heavy that it is not convenient to provide a primary integral with the transformer and the latter then consists of an iron core of appropriate shape with a secondary winding thereon, the whole being mounted on the busbar or cable. The nominal full-load current of a transformer is termed the "rated primary current" and is the value in amperes of the primary current marked on the rating plate.

The secondary winding of a current transformer is usually constructed to deliver five amperes to the meter or instrument when rated primary current flows in the main circuit. This is referred to as the "rated secondary current" and five amperes is the standard value adopted in most countries. In power-station practice it is not unusual for the meter to be separated from its current transformers by a distance of several hundred feet. The I^2R loss in the connecting leads together

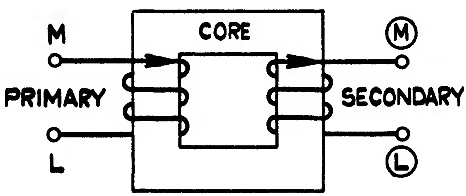


FIG. 194.—Magnetic and electric circuits of a current transformer.

with the loss in the meter current coils may impose a burden in excess of the transformer rating if a five-ampere secondary current is adhered to. By adopting a lower value for the rated secondary current the loss in the leads can be substantially reduced and one ampere or 0·5 ampere values are permissible alternatives. Since the loss varies as the square of the current the adoption of one of these alternatives will reduce the loss in the leads to one-twenty-fifth or one-hundredth of the original value respectively.

The magnetic and electric circuits of a current transformer are represented diagrammatically in Fig. 194; the primary winding is shown surrounding one limb of the core and the secondary winding surrounding another. In actual practice the two windings would not be separated in this manner as the primary would be superimposed on the secondary, but they are shown thus for the sake of clarity in the diagram. The primary terminals are indicated by the letters M and L, and the secondary terminals by the same letters enclosed in a circle.

The cores of current transformers are usually built up with laminations of silicon-steel but where a high degree of accuracy is desired a high-permeability nickel-steel such as Mumetal or Permalloy may be used. Three types of magnetic circuit are in common use, namely, "ring type", "core type" and "shell type" and are illustrated in Fig. 195.

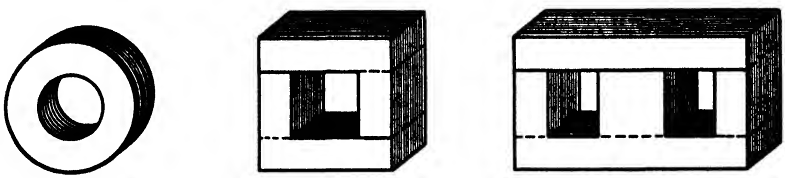
12.3. Ring Type Current Transformers. Ring type current transformers are employed where the primary conductor consists of a round bar or cable, or where the insulation surrounding the primary is in the form of a round tube. The ring stampings are built up into a core of the required thickness, between two rings of insulating material. If the transformer core is large and heavy these rings may consist of plywood the outer edges of which are rounded in order to avoid sharp bends in the secondary winding. The core and rings are covered with several layers of cotton tape which is applied under tension to form a compact whole.

The secondary winding is distributed evenly around the core and may consist of one or several layers. Should the transformer be intended for use in a situation where heavy overloads or short circuits are likely to be encountered, care must be taken to insulate adequately between adjacent layers, otherwise internal short circuits may develop in the winding due to momentary high voltages induced under fault conditions. This is particularly important in transformers having one-ampere or 0·5-ampere secondaries, as these frequently have a large number of turns in the windings. In such cases it is preferable to subdivide the secondary into a number of sections wound side by side, each section having a small number of turns wound in several layers.

12.4. Core Type Current Transformers. Core type current transformers are built up from stampings, usually of **L**-shape, two of which when laid together form a hollow rectangle and complete the magnetic circuit. Alternatively a pair of stampings may comprise one of ⊔-shape and one of ▬-shape, the ▬ being laid across the extremities of the ⊔ to complete the magnetic circuit. The core is built up with pairs of stampings so arranged that the joints occupy different positions in alternate layers. This is shown in Fig. 195 where the **L**-shape stampings are used. The joints in the top layer are indicated by solid lines and in the next layer by dotted lines. Core type transformers for mounting on large busbars may consist entirely of ▬-shape strips assembled four per layer in the form of a rectangle, with joints at each corner overlapping in alternate layers.

The secondary winding consists of one, two or four coils, connected in series and mounted on one, two or four limbs of the core respectively. The advantage of the joints in the core is that this construction permits former-wound coils to be used. The winding and insulating of a former-wound coil is a much simpler operation than the hand-winding process on a ring type transformer. On the other hand, the presence of joints in the magnetic circuit may in some cases impair the accuracy of the transformer.

The primary windings of core type transformers for low voltages are usually former-wound and insulation in the form of varnished cotton tape is applied over the winding which is then impregnated in insulating varnish by a vacuum process. High-voltage windings may also be insulated in a similar manner but with a greater thickness of insulation. For voltages in excess of 6,600 volts the core and winding



Ring type. Core type. Shell type.

FIG. 195.—Types of magnetic circuit for a current transformer.

may be immersed in insulating oil or compound; alternatively the primary windings of high-voltage transformers are enclosed in tubes of porcelain or bakelite and in the case of bar-type primaries such tubes may be utilized irrespective of the voltage.

12.5. Shell Type Current Transformers. Shell type current transformers are built up from pairs of stampings, the one being ɯ-shape and the other ▬-shape. These when laid together form a magnetic circuit comprising two branches, the middle limb being common to both. As in the core type, the stampings are placed so that the joints occupy different positions in alternate layers as shown in Fig. 195. The primary and secondary windings are placed on the middle limb, the secondary being inside the primary. The middle is usually wider than the outer limbs as it carries the total magnetic flux which divides equally between the outer limbs.

The shell type construction is usually limited to transformers for voltages not exceeding 11,000 volts and in which varnished cotton

tape or similar material is used as the main insulation for the primary winding. Since the windings are always placed on the middle limb and are embraced by the outer limbs, they are better protected mechanically than the windings of a core type transformer. Moreover, since it can be securely wedged in position, the primary winding is more firmly supported to resist forces tending to disrupt or displace it, in the event of a severe short circuit on the line. A primary consisting of a single turn must pass in opposite directions through both openings in the core and consequently is more or less U-shape. Because of this necessity, a shell type transformer cannot be used in a busbar run and the maximum primary current for which it can be conveniently constructed is of the order of 600 to 800 amperes.

12.6. Multi-Range Current Transformers. In electrical laboratories and test-rooms, multi-range transformers are used to provide a wide range of measurement on a single instrument or meter. A single transformer can be constructed to provide a number of ranges by means of a tapped primary coil, a tapped secondary coil, a series-parallel arrangement of primary coils, or a combination of two or more of these alternatives.

A tapped primary coil may be used where the current ranges required are comparatively few and the ratios close together, as for example 200–150–100/5 amperes. It is not usual to provide a tapped primary for currents much in excess of 200 amperes or for ranges where the highest ratio is more than double that of the lowest. Constructional difficulties usually limit the practicability of providing the higher ratios, and variation in the characteristics limits the divergence between the extreme ranges.

A tapped secondary coil can be used to provide several ranges on a transformer with a single primary and is particularly useful where heavy currents are involved. For example, ratios of 1,000–800–600–500/5 amperes can be supplied without difficulty and as in the case of a tapped primary, variation in characteristics limits the total range covered by this method. The lowest ratio should not be less than half the highest if reasonable concordance is desired.

A series-parallel arrangement of primary coils permits a wider range of measurement to be covered. For example, a primary consisting of four similar sections can be arranged to give ratios of 800–400–200/5 amperes. With four sections, in parallel the ratio will be 800/5 amperes; with four in series 200/5 amperes, and with two sets in series-parallel 400/5 amperes. This arrangement is more flexible than the tapped

winding as the highest ratio is four times the magnitude of the lowest and there is the further advantage that the accuracy of the transformer is substantially the same on all ratios. In addition, high ratios are handled just as conveniently as low and an example of the latter has ratios of 40–20–10/5 amperes. It will be noted that the ratios obtainable by means of series-parallel connections must be in the proportions 4: 2: 1 in a triple-range transformer and 2: 1 in a dual-range. On the other hand, a tapped secondary permits an odd ratio to be accommodated which cannot be obtained by any other means.

Separate primary coils co-operating with a single secondary can be made to cover a wide range of measurement. For example, a transformer having ranges of 600–150–30/5 amperes can be made and in fact several intermediate ranges could be incorporated if necessary. The current rating of each range must correspond to a number which is divisible into the highest range without a remainder as in the example. The accuracy of the transformer will be substantially the same on all ranges if the secondary is not tapped. If, however, the secondary is tapped, a single tapping would provide additional ratios such as 500–125–25/5 amperes in the example above. The errors on these additional ranges will be similar amongst themselves but will differ slightly from the errors on the other ranges first mentioned. By a combination of separate primary coils and tapped secondary coil, a transformer can be made which will have a large number of ratios covering all essential requirements in a single unit.

12.7. Summation Current Transformers. Where current is supplied through a number of separate feeders to some central situation, it is sometimes desired to know the total power transmitted at any instant. Thus, it may be necessary to know the total output of several generators feeding on to one set of busbars, or the maximum demand of a large manufacturing organization receiving supplies through a group of feeders. In such a case a transformer core wound with several primaries and a single secondary may be used. Each primary is connected in series with a generator or feeder as the case may be, and the combined effect of all the primaries acting upon the one secondary enables a single instrument to indicate the sum of the individual loads on the separate circuits; a transformer constructed in this manner is known as a summation transformer.

In practice it is usually inconvenient for a number of high-voltage primaries to be wound on one core since each must be insulated from the others and a very bulky transformer would result. Moreover for

technical reasons it is not permissible to bring together at a single point several high-voltage bars or cables from separate sources. Accordingly the primary windings of a summation transformer are energized from the 5-ampere secondaries of high-voltage current transformers, one in each of the circuits which it is desired to summate. Thus, a summation transformer usually occupies a second stage in the transformation.

The number of turns on each of the primaries of a summation transformer will be in proportion to the rated primary currents of the corresponding transformers in the circuits to be metered. If it is desired to summate the current in four feeders having current transformers of ratios 400/5, 300/5, 200/5 and 100/5 amperes respectively, the summation transformer could have four corresponding primaries wound with 80, 60, 40 and 20 turns. This would provide a total of 1,000 ampere-turns on the core when all the primaries were carrying rated current. The current in the secondary of the summation transformer is proportional to the vector sum of the currents in the primaries of the transformers feeding the summation transformer which latter, in the example quoted, would be rated as 400 + 300 + 200 + 100/5 amperes. The equivalent ratio of this transformer would be 1,000/5 amperes.

12.8. Portable Current Transformers. The majority of current transformers in use are installed permanently in switchgear or industrial installations for the operation of electrical instruments or meters and are of single ratio. In laboratories and test-rooms and for general testing work, portable or transportable current transformers are used extensively, and these vary in accuracy from grades which cannot be assigned to any recognized class, to precision grades in which errors over a wide range of measurement are extremely small. In order to extend their sphere of usefulness many of these transformers are of the multi-range variety. One of the crudest forms of current transformer is that which is associated with a so-called "clip-on" ammeter. It consists of a U-shaped laminated core on which a secondary coil is wound, this coil being connected to an ammeter. A hinged yoke-piece completes the magnetic circuit across the extremities of the U, making two butt joints therewith. The ammeter and transformer are attached to a handle and a trigger device separates the yoke piece from the core to enable the latter to be placed around a conductor such as a cable in which it is desired to measure the current flowing. Spring pressure is then applied to hold the yoke against the extremities of the core. Because of the inevitably poor joints in the magnetic circuit, the

errors of such a transformer are large, but as the ammeter is calibrated with its transformer, the errors of the latter are disguised and the indications of the instrument may be approximately correct over a short range.

At the other extremity is the precision-grade current transformer having a "Mumetal" core in the form of a jointless ring, the secondary being distributed uniformly around the core. Several primaries may be wound over the secondary to give a choice of current ratios, and a series-parallel arrangement of primary sections may also be used. The transformer may be mounted in a box or case leaving a tubular opening through the centre of the core. This permits a flexible conductor to be threaded through the tube and a number of additional ratios are made available by varying the number of turns passed through the opening. Multi-range precision grade current transformers frequently have a large number of primary ampere-turns varying between 600 and 1,200 but can in fact be made with a much smaller number of ampere-turns in cases where a few ranges only are required and where the maximum current range is less than 600 amperes. Apart from their usefulness in extending the range of wattmeters and watt-hour meters, they are used extensively as standards of comparison in the determination of the errors of ratio and phase angle in other current transformers of all grades of accuracy.

12.9. Theory of Current Transformers. A current transformer is similar in construction to a power transformer in that it has a magnetic circuit with which is linked a primary and a secondary winding. The method of operation, however, differs considerably. In a power transformer the primary winding is continuously energized at a substantially constant voltage, and the secondary is connected to a load which may vary in resistance or impedance within wide limits. The current in the primary winding at any instant is determined by the amount of load connected to the secondary. The magnetic flux in the core is substantially constant at all loads.

The current transformer on the other hand is connected in the line in series with the load and it is the latter which determines the current passing in the primary winding. The secondary is connected to a load or burden which does not vary, and the primary current is not influenced by the magnitude of the secondary load: the current in the secondary is determined by the current in the primary. The magnetic flux in the core varies with the current in the primary winding; the magnitude of this flux is determined by the connected burden and the

induction density in the core is only a very small fraction of that usually employed in a power transformer.

The vector diagram in Fig. 196 shows the relationship which exists between the various components of the primary and secondary currents, the core flux and the character of the secondary burden, in a current transformer. A nominal ratio of 5/5 amperes is assumed as a matter of convenience.

The secondary current I_S lags behind the secondary induced voltage E_S by an angle ϕ. This angle is determined by the impedance of the

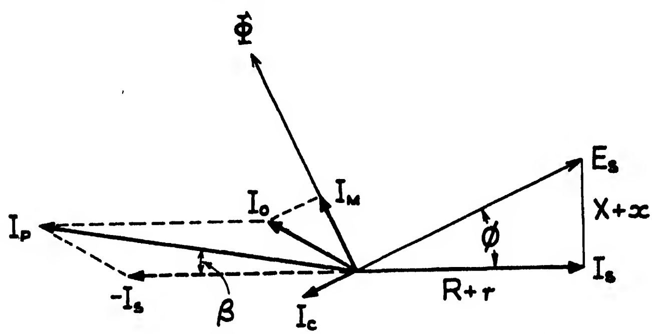


FIG. 196.—Vector diagram for current transformer.

I_p = primary current.
I_s = secondary current.
I_m = magnetizing current.
I_0 = exciting current.
I_c = core loss current.
Φ = core flux.
ϕ = phase difference between secondary current and voltage.
R = resistance of burden.
r = resistance of secondary.
X = reactance of burden.
x = reactance of secondary.
E_s = secondary induced e.m.f.
β = phase angle.

external burden connected to the transformer and the impedance of the secondary winding. The total impedance of the secondary circuit is proportional to $\sqrt{(R + r)^2 + (X + x)^2}$.

The secondary voltage E_S lags 90 deg. behind the core flux Φ which latter is produced by the magnetizing current I_M in phase with Φ, and the core loss current I_C 90 deg. in advance of Φ. The total exciting current I_O is the resultant of the two components I_M and I_C, and the magnitudes of these components determine the ratio and phase displacement errors of the transformer.

The primary current I_P is the resultant of the reversed secondary current $-I_S$ (shown by the dotted line) and the exciting current I_O. The angle β between I_P and $-I_S$ expressed in minutes of arc is t

phase displacement error of the transformer and the difference between the lengths of I_P and $-I_S$ (when the angle β is small) expressed as a percentage of I_P is the ratio error.

Variations in the primary current produce corresponding variations in primary ampere-turns and consequently in the core flux. Since the permeability of the iron core is not constant at all inductions, the exciting current required for magnetizing the core will not be proportional to the primary current. This departure from proportionality results in the errors of the transformer varying with different primary currents. At very low inductions the permeability is also low and accordingly a larger proportion of exciting current is necessary in order to magnetize the core. Current transformers are usually designed to give their best performance between 10 per cent. and 120 per cent. of rated primary current (see Tables 10 and 11).

The variations in the errors of a current transformer are at a minimum with a small external burden and increase as the burden increases. The greater the burden, the greater will be the secondary voltage required to overcome its impedance, and consequently the greater the magnitude of the core flux and the exciting current. From a study of Fig. 196 it will be evident that with a given primary current I_P, any change in the exciting current I_O will result in a change in the phase displacement β or the secondary current reversed $-I_S$ or both.

In order to minimize errors in ratio and phase displacement the exciting current must be kept relatively small. This is accomplished by making the magnetic circuit as short as possible in order to reduce its reluctance. The primary ampere-turns at rated current must be high in order to reduce the induction in the core, and the primary and secondary windings must be in close proximity in order to reduce magnetic leakage. On the other hand the primary ampere-turns must be low in order to avoid destructive influences under short-circuit conditions; the windings must be well separated to permit adequate insulation particularly on high voltages, and the length of the core must be sufficient to accommodate the windings with their coverings of insulation. Thus, the conditions necessary to ensure accuracy may conflict with the requirements for safety, and the design of the transformer becomes a compromise depending upon the relative importance of the various factors.

For the manufacture of the core stampings, the use of alloy steel having a high nickel content enables some of these conflicting requirements to be met. Steels such as Mumetal and Permalloy having a much

higher permeability than the more usual silicon steel are frequently employed where low ampere-turn primaries or relatively long magnetic circuits are unavoidable. Such steels however are very expensive and are only employed as a rule when accuracy is important and is not otherwise attainable.

12.10. Burden of Current Transformers. The burden of a current transformer is the value of the load connected across the secondary terminals expressed as the output in volt-amperes. The rated burden is the value of the burden marked on the rating plate. The burden may consist of a meter or an instrument, or a collection of such, and where more than one is in use all are connected in series. The aggregate volt-ampere consumption in all the meters and instruments connected to a transformer, together with the losses in the connecting leads, should never exceed the rated volt-amperes, otherwise errors in excess of the permissible limits may be introduced. This statement does not imply that a transformer is incapable of carrying a burden in excess of its rating, because in fact, most transformers will carry many times their rated burden, but the effect of connecting an excessive burden is to increase the errors beyond the limits applicable to the class designation of the transformer in question.

The British Standard Specification for Instrument Transformers,

TABLE 10

Current Transformer Classes and Rated Burdens

Class	Rated Burden in Volt-Amperes				Application
A	2½	5	15	—	Indicating
B	2½	5	15	—	and
C	2½	5	15	—	recording
D	2½	5	15	—	instruments
AM	2½	5	15	30	Integrating
BM	2½	5	15	30	meters
CM	1½	5	15	—	
AL	—	7½	—	—	Laboratory
BL	—	7½	—	—	instruments

B.S. 81: 1936, classifies current transformers according to their suitability for specific purposes and lists the rated burdens for which they are constructed. There are nine different classes of current transformers as listed in Table 10, and each class with the exception of AL and BL is intended to be manufactured to cover a range of rated burdens. For measuring instruments (indicating and recording), Classes A, B, C and D are provided, the permissible errors being smallest in Class A and progressively greater in Classes B, C and D. Portable instrument transformers in Classes AL and BL are intended for use with laboratory instruments and the accuracies laid down for these classes are not normally applicable to instrument transformers for other purposes. Classes AM, BM and CM are intended for use with integrating meters (kWh meters and the like) and these have to fulfil conditions which are not necessary in transformers for indicating instruments. Reference to these special conditions is made in Section 12.11.

A current transformer is usually designed to deliver its rated burden at the supply frequency marked on the rating plate. In this country the standard frequency is 50 cycles per second and if a transformer is used on a frequency differing from that for which it is designed, the rated burden will also be different. Generally speaking, an increase in frequency will result in a small increase in the permissible burden while a reduction in frequency will always result in a reduction in the permissible burden. A change for example, from 50 to 25 cycles per second will reduce the rated burden to approximately 40 per cent. of the nominal value.

The maximum burden which a current transformer can supply in any particular class is dependent upon its ampere-turns at rated primary current. The higher the accuracy required and the greater the burden to be sustained, the greater will be the ampere-turns necessary. In practice, the ampere-turns employed vary between 100 and 1,000, and in transformers having silicon-steel cores, 600 ampere-turns are commonly employed to give Class B accuracy with an output of 15 volt-amperes. By using a jointless ring core of Mumetal, the same accuracy may be obtained in an extreme case with 200 ampere-turns, but such a transformer would be comparatively costly and commercial considerations usually favour the employment of more orthodox designs in which the necessity for limitation of ampere-turns does not arise.

12.11. Errors in Current Transformers. One of the functions of a current transformer is to deliver to the meter or instrument connected to its secondary winding, a current, the magnitude of which is proportional

to the current flowing through its primary winding. Further, the current in the secondary should coincide in phase with the primary current. The amount by which the secondary current differs from exact proportionality to the primary current is called the ratio error and is expressed as a percentage of the rated secondary current. The angle by which the secondary current differs in phase from the primary current is called the phase difference error and is expressed in minutes of arc.

In an ideal transformer there would be exact proportionality between primary and secondary currents at all loads and, in like manner, exact coincidence in phase relationship. In practice this ideal cannot be achieved although a very close approach has been made, and precision transformers are obtainable in which the errors over a wide range of current are of negligible proportions.

The permissible limits of error for current transformers are laid down in B.S. 81: 1936, Clause 17, which states that the ratio error and the phase difference between the currents in the primary and secondary windings of a current transformer when tested at rated burden, at unity power factor and at rated frequency, shall not exceed the limits in Tables 11 and 12 which follow. It will be noted from these tables that limits of error are given for a range of current varying from 120 per cent. to 10 per cent. of rated current. Rated current is defined as

TABLE 11

Limits of Error for Metering Current Transformers

Class	Absolute Error				Variation in Error	
	From 120% to 20% of Rated Current		Below 20% to 10% of Rated Current		From 120% to 10% of Rated Current	
	Ratio	Phase Diff.	Ratio	Phase Diff.	Ratio	Phase Diff.
	+ or −	+ or −	+ or −	+ or −	+ or −	+ or −
AM	1·0%	30 min.	1·0%	30 min.	0·5%	15 min.
BM	1·0%	35 „	1·5%	50 „	1·0%	25 „
CM	1·0%	90 „	2·0%	120 „	1·5%	60 „

the value of the primary current marked on the rating plate. The ratio error is given as a percentage and the phase difference error as minutes of angular displacement.

In specifying limits of error, it is important to note that, in the case of metering current transformers, a limit is also imposed on the variation in the error. In calibrating a meter for use with current transformers it is possible by means of the magnet adjustment to raise or lower the curve as a whole and thus to compensate for a ratio error in the transformer. There is, however, no adjustment which will permit any

TABLE 12

Limits of Error for Current Transformers used with Measuring Instruments for Laboratory (AL and BL) or General Use (A, B, C and D)

Class	Absolute Error					
	From 120% to 60% of Rated Current		Below 60% to 20% of Rated Current		Below 20% to 10% of Rated Current	
	Ratio	Phase Diff.	Ratio	Phase Diff.	Ratio	Phase Diff.
	+ or −	+ or −	+ or −	+ or −	+ or −	+ or −
AL	0·15%	3 min.	0·15%	4 min.	0·15%	6 min.
BL	0·3%	10 ,,	0·4%	15 ,,	0·5%	20 ,,
A	0·5%	35 ,,	0·5%	35 ,,	1·0%	50 ,,
B	1·0%	60 ,,	1·0%	60 ,,	1·5%	90 ,,
C	1·0%	120 ,,	1·0%	120 ,,	2·0%	180 ,,
D	5·0%	—	5·0%	—	—	—

appreciable alteration in the shape of the meter curve between 120 per cent. and 10 per cent. rated current at unity power-factor. If therefore the transformer error varies within this range the same variation will be reproduced in the meter curve. Similarly, by means of the quadrature adjustment, correction can be made on the meter for the phase displacement error of the transformer, but if this error varies with the load then the corrections can be made at one load only. From the

foregoing it will be appreciated that the variations in the errors of a current transformer are actually more important to the meter engineer than the absolute values of the errors, since the latter can be eliminated in combined calibration, whereas the variations cannot.

12.12. Over-current Rating of Current Transformers. The over-current rating of a current transformer is represented by a number which gives an indication of the capacity of the transformer to withstand the effects of excessive current passing through its windings. In generating stations and on distribution systems, a short-circuit under present-day conditions may give rise to currents of very considerable magnitude, particularly in cases where, owing to interconnection of lines or feeders, a number of power stations may feed into the fault. The effects on a transformer subjected to these excessive currents are twofold; on the one hand, mechanical stresses may be set up tending to disrupt the transformer and on the other, overheating of the windings may occur tending to damage or destroy the insulation.

The instrument transformer specification B.S. 81: 1936 requires that a current transformer (other than portable type) provided with a primary, shall be marked on the rating plate with the over-current factor expressed thus (for example): O.C.F. 100 for 0·5 secs. This information enables the user, knowing the maximum over-current and its duration likely to be experienced in any given situation, to decide whether the transformer is capable of withstanding the operating conditions with safety. Further, should the conditions at a later date become more severe a check will reveal whether the transformer can safely be retained in service.

The relevant portions of the specification which deal with over-current rating are contained in Clause 18, extracts from which are as follows:

1. "A rated over-current factor shall be assigned to the transformer by the Manufacturer such that the rated primary over-current (average R.M.S. value throughout the rated time) is equal to the product of the rated primary current (R.M.S. value) and the rated over-current factor."
2. "The initial asymmetrical peak value of the rated primary over-current for the purpose of this Clause shall be 2½ times the product of the rated primary current and the rated over-current factor."
3. "If a current equal to the product of the rated primary current

and the rated over-current factor is passed for the rated time through the primary of the transformer, the secondary of which is connected to the rated burden, the temperature rise shall not exceed 200 deg. C. in any part of the transformer."

4. "When a current having an initial peak value of $2\frac{1}{2}$ times the product of the rated primary current and the rated over-current factor is passed through the primary of the transformer, the secondary of which is connected to the rated burden, the electromagnetic forces involved shall not cause electrical or mechanical damage to the transformer."

As stated in the second paragraph of this extract, the initial asymmetrical peak value of the rated primary current is assumed to be 2·5 times the product of the rated primary current and the rated over-current factor. The factor 2·5 is the product $\sqrt{2} \times 1{\cdot}8$: where $\sqrt{2}$ is the peak factor of a sine wave and 1·8 is the maximum probable displacement factor of the first half-wave of an asymmetrical over-current. The rated time referred to in the first and third paragraphs of the extract is the maximum duration of the over-current for which the transformer is constructed; the usually accepted standard for rated time is 0·5 sec. but longer periods may be permissible in exceptional circumstances. Other things being equal, an increase in the rated time necessitates a reduction of the current density in the primary, with a consequent increase in the dimensions of the transformer.

Mechanical damage resulting from an over-current is due to the electromagnetic forces set up. The maximum stress coincides with the initial current peak which occurs practically at the instant of short-circuit. The waveform of the current at the initiation of a short-circuit is usually asymmetrical, that is, the positive and negative half-waves are not symmetrically disposed about the zero line. The first cycle of current may be almost entirely displaced to one side of the zero line, but succeeding cycles gradually become more symmetrical and after the passage of say twenty cycles, the fault current, if not interrupted, assumes a normal steady value. The magnitude of the electro-magnetic force is proportional to the square of the current amplitude, the square of the number of turns and the configuration of the coil structure.

It will be clear from the foregoing what the most destructive electromagnetic force is developed during the first complete cycle of current following the initiation of a short-circuit, and it is during this short interval that a risk of mechanical damage may be incurred. The rated

time is therefore not an important factor insofar as this risk is concerned. If the transformer survives the initial shock due to a short-circuit it may still suffer damage should the duration of the over-current be sufficient to cause excessive temperature rise in the primary winding and it is in this connection that the rated time is important.

When a current transformer suffers mechanical damage as a result of an over-current the primary winding is usually deformed or displaced. A wound primary, whatever its configuration, tends to become enlarged until its perimeter encloses the largest possible area. A circle encloses a greater area than any other figure for a given perimeter, and consequently the tendency is always for the primary to become circular. It follows that a primary which is already circular will exhibit less tendency to deform than any other shape of multi-turn winding, and if this construction is not possible, then ample support must be provided where necessary to resist deformation. A primary consisting of a rectangle having two long parallel sides (sometimes referred to as a trombone pattern), is inherently very weak, but is commonly used in high-voltage circuits where a comparatively low over-current factor is permissible. If there is any possibility of axial movement, mutual repulsion may force the primary of a transformer along the core in one direction and the secondary in the opposite direction.

The secondary coil is not usually a source of weakness as regards ability to withstand the effects of an over-current, apart from the possibility of axial movement, and this can usually be avoided by wedging it securely in position on the core. Magnetic saturation of the core limits the magnitude of the induced current to perhaps twenty times the rated value and this is insufficient to cause distortion or serious overheating in the short interval during which the over-current persists.

Commercial types of current transformer may be expected to have a rated over-current factor between 50 and 100 based on a rated time of 0·5 second, without any special precautions being taken in their design. Transformers having over-current factors of 200 to 400 can also be produced with reasonable facility for the same rated time. For an over-current factor in excess of 400, a bar primary is usually essential; under over-current conditions a bar primary exhibits no tendency to deformation and consequently this is the strongest and safest form. Unfortunately it is not always possible to achieve the class of accuracy or the burden desired when a bar-type transformer is used, since the primary has the equivalent of but a single turn, and the primary ampere-turns are therefore equal to the rated primary current.

Bar-type current transformers can be made for currents as low as 100 amperes, but become very costly if accuracy is required. Safety under operating conditions is usually an overriding factor and accuracy or burden or both must be sacrificed in the interests of security.

12.13. Effect of Open Secondary Circuit. Under normal operating conditions the secondary winding of a current transformer is connected to its burden and the secondary circuit is always closed. When current flows through the primary winding a current also flows in the secondary and the ampere-turns of each winding are substantially equal and opposite. In practice, the secondary ampere-turns will be actually from one per cent. to two per cent. less than the primary ampere-turns, the difference being utilized in magnetizing the core. Thus, in a current transformer having a ratio of 600/5 amperes, the ampere-turns necessary for excitation will be of the order of 6 to 12, the exact number depending upon the magnitude of the connected burden and other factors. If now, this transformer is carrying 600 amperes and the secondary circuit is interrupted, the core will immediately be subjected to 600 ampere-turns.

Assuming that the connected burden is 15 VA and that the internal burden of the transformer is 5 VA making a total of 20 VA, then the e.m.f. necessary to force 5 amperes through this total burden will be 4 volts. Assuming further that 10 ampere-turns are necessary for supplying this burden, it follows that when the core excitation is raised from 10 to 600 ampere-turns, that is to 60 times the normal, the secondary induced voltage may increase in the same proportion.

As a matter of fact the core will probably be saturated by the enormous increase in excitation, in which case the waveform of secondary e.m.f. will no longer be sinusoidal; the peak voltage in these circumstances will be several times the R.M.S. value and may easily be 600 volts or more. In the case of transformers having 1-ampere or 0·5-ampere secondary windings the turns will be increased fivefold or tenfold with a corresponding increase in the induced e.m.f. to 3,000 or 6,000 volts, or more. Such potentials are a danger to life and there is also the risk of damage to the insulation between turns of the winding or between the winding and the core. It is clear, therefore, that the secondary circuit of a current transformer should never be open when the primary is carrying current.

Apart from the foregoing, the saturation of the core will in some cases have a prolonged and detrimental effect on the accuracy of the transformer, due to a change in the magnetic characteristics. This

change can be nullified by demagnetization, but the process is not easily applied to a transformer after installation. In addition, if the open circuit condition persists, excessive heating of the core will follow owing to the severe hysteresis and eddy current losses resulting from the high induction in the iron.

The risk of an open circuit in the secondary is perhaps greater in the case of portable or testing current transformers than in other types, owing to momentary forgetfulness on the part of the tester. The risk of accidental contact is also greater, and because of this it is a common practice to provide a short-circuiting switch across the secondary terminals. The switch should normally remain closed until it is necessary to take a reading on the instrument connected to the transformer. The short-circuiting switch also facilitates the exchange of an instrument

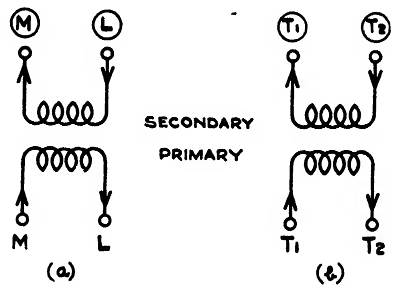


FIG. 197.—Terminal markings of current transformers with plain windings.

during a test, or the withdrawal of plugs or links to change the current range of a wattmeter should this be necessary, in the case where the instrument is connected to the secondary of a current transformer.

12.14. Terminal Markings of Current Transformers. In order to distinguish clearly between the primary and secondary windings of current transformers and to indicate the respective polarities, standard systems of terminal markings are in use. Details of these markings will be found in the British Standard Specification B.S. 81: 1936, Clause 13 and also in Appendix K. The primary terminals are distinguished by the use of capital letters, with or without the addition of numerals. The secondary terminals are distinguished by capital letters, with or without the addition of numerals, and contained in a circle.

The basic idea underlying the systems of marking is indicated in Fig. 197 (a) and (b) which shows plain primary and secondary windings.

In Fig. 197 (a) the primary terminals are marked M L and the secondary terminals bear similar letters each enclosed in a circle as shown in the diagram. At the instant when the current in the primary is from M to L, the current in the secondary external circuit or burden is from M (encircled) to L (encircled). Similarly in Fig. 197(b) the primary terminals are marked T_1 T_2 with corresponding markings (encircled) on the secondary terminals. The arrows in the diagram indicate the direction of current at a given instant.

Both these systems of marking are in use in this country, some manufacturers preferring one and some the other. The letters M L have long ago acquired a significance amongst meter engineers as indicating "Main" and "Load", and consequently the majority of meter manufacturers adhere to the use of these letters in the marking

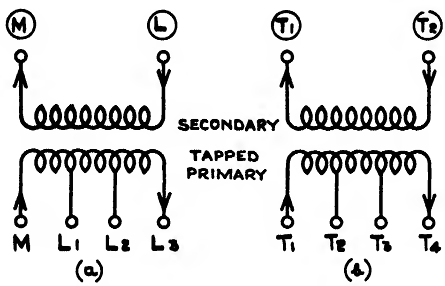


FIG. 198.—Terminal markings of current transformers with tapped primaries.

of the transformers they supply with their meters. This significance however does not necessarily apply in the case of transformers, which can if desired be connected in the opposite sense without detriment as the marking is purely directional.

The markings of current transformers with tapped primaries are shown in Fig. 198 (a) and (b). It will be noted that numerals are used as suffixes on the tappings. The tapping embracing the smallest section of the winding carries the lowest numeral and the extremity of the winding has the highest numeral. Current transformers with tapped secondary are shown in Fig. 199 (a) and (b) and the same principles govern the numbering of the tappings as in the case of transformers with tapped primary. Current transformers with double secondary are shown in Fig. 200 (a) and (b). In the case of Fig. 200 (a) it will be noted that one secondary carries the suffix "1" and the other the suffix "2".

In Fig. 200 (b) one secondary includes a suffix "a" and the other a suffix "b" in addition to a numeral. Several additional diagrams are included in B.S. 81: 1936 but are not reproduced here. Sufficient examples have been given to enable the principles involved in the

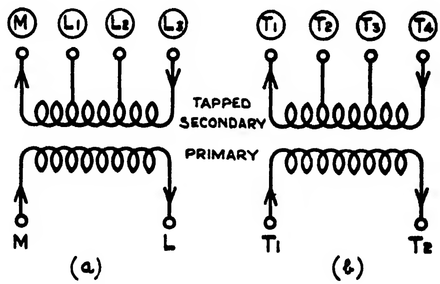


FIG. 199.—Terminal markings of current transformers with tapped secondaries.

terminal marking system to be understood, and the application of these principles can be extended to any other arrangement of windings.

12.15. Typical Performance Data. In the Tables which follow, figures are given to illustrate the variations of ratio and phase displacement

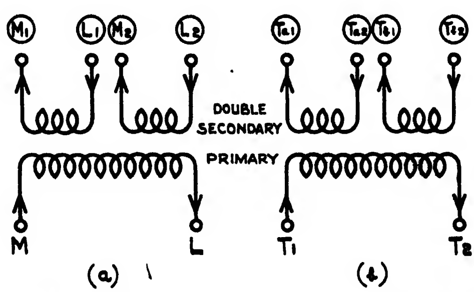


FIG. 200.—Terminal markings of current transformers with double secondaries.

which arise in practice as a result of variations in primary current or secondary burden. The tests have been carried out on several classes of current transformer and the results may be compared with the limits of error specified in B.S. 81: 1936, details of which are given in Tables 11 and 12 on pages 423 and 424 respectively. All the transformers to which these tests relate were manufactured by Chamberlain and Hookham Ltd.

The figures in Table 13 relate to a shell-type current transformer having a ratio of 300/5 amperes and insulated for use on a 6,600 volt, 50 c/s system with earthed neutral. The primary winding consists of two turns and the secondary winding of 119 turns, the rated burden being 15 VA Class CM. The maker's designation is Type HTA. It may be observed that with a burden of 5 VA the performance would comply with the limits of error specified for Class BM, and with a burden of 30 VA the limits for Class C are not exceeded. With increasing burden the ratio error becomes progressively more negative in value and the phase angle becomes larger. These effects are more pronounced at the lower primary currents.

The figures in Table 14 relate to a ring-type precision current transformer, Class AL, ratio 800/5 amperes, rated at 7·5 VA. 50 c/s and tested at burdens of 5, 15 and 40 VA. The range of primary current covered by B.S. 81: 1936 for these tests is from 120 per cent. to 10 per cent of rated current, but in this instance a wider range from 125 per cent. to 5 per cent. was covered with good results. The absence of any variation in the ratio error over the whole range of primary current at each burden and also the small variation in the phase angle is noteworthy. The tests at 40 VA exceed five times the rated burden for which the transformer was constructed, but the results still fall well within the limits of error for a Class BL transformer.

Test results on a ring-type multi-ratio precision current transformer, Class AL, are given in Table 15. The transformer has seven separate primary windings giving current ratios of 1–2·5–5–10–25–50–100/5 amperes, any one of which can be selected by means of a sector switch; in addition, provision is made for the insertion of one or more primary turns through a tube on which the ring core is mounted. With a single turn or bar primary passing through the tube, additional ratios of 750/5 and 1,000/5 amperes may be obtained, a tapped secondary winding enabling this dual ratio to be effected. By increasing the number of inserted turns, proportionately lower ratios can be obtained as for example, five turns will give ratios of 150/5 and 200/5 amperes respectively. No change in the error is observable when the number of turns is altered.

Attention may be drawn to the very small errors in ratio and phase displacement and to the fact that the phase error is divided between 1·1 minutes lagging and 1·0 minute leading. All the tests referred to in Tables 13, 14 and 15 were carried out with non-inductive burdens.

TABLE 13

Tests on Metering Current Transformer showing the effect of increasing burden on the Accuracy Classification obtainable

Primary Current in per cent. of Full Load	Errors in Ratio and Phase Angle (Leading)					
	Burden 5 VA		Burden 15 VA		Burden 30 VA	
	Ratio	Phase	Ratio	Phase	Ratio	Phase
%	%	min.	%	min.	%	min.
120	+0·29	14	+0·15	22	—0·06	30
100	+0·25	15	+0·10	24	—0·12	33
50	+0·13	22	—0·03	37	—0·26	49
20	—0·08	33	—0·28	60	—0·56	83
10	—0·19	39	—0·40	74	—0·70	104
Variation in error	0·48	25	0·55	52	0·64	74
Category	Class BM		Class CM		Class C	

TABLE 14

Tests on Precision Current Transformer showing the Effects of a Change of Burden over a Wide Range of Primary Current

Primary Current in per cent. of Full Load	Errors in Ratio and Phase Angle (Leading)					
	Burden 5 VA		Burden 15 VA		Burden 40 VA	
	Ratio	Phase	Ratio	Phase	Ratio	Phase
%	%	min.	%	min.	%	min.
125	—0·05	2	—0·10	3	—0·25	4
100	—0·05	2	—0·10	3	—0·25	5
20	—0·05	3	—0·10	5	—0·25	9
10	—0·05	3	—0·10	6	—0·25	11
5	—0·05	4	—0·10	7	—0·25	13

TABLE 15

Tests on Multi-Ratio Portable Precision Current Transformer with Constant Burden of 7·5 VA

Primary Current in per cent. of Full Load	Errors in Ratio and Phase Angle					
	All wound primaries		750 amp. bar primary		1,000 amp. bar primary	
	Ratio	Phase	Ratio	Phase	Ratio	Phase
%	%	min.	%	min.	%	min.
120	—0·04	—1·1	—0·04	—0·8	—0·02	—0·2
100	—0·04	—0·8	—0·03	—0·7	—0·02	—0·1
60	—0·04	—0·3	—0·03	—0·2	—0·02	+0·2
20	—0·03	+0·6	—0·02	+0·6	—0·01	+0·7
10	—0·02	+1·0	—0·02	+0·9	—0·01	+1·0

In the columns showing the phase displacement error in the above Table, the + sign indicates a leading angle and the — sign a lagging angle.

CHAPTER XIII

VOLTAGE TRANSFORMERS

13.1. Why Voltage Transformers are used. When an instrument or meter having a voltage winding is connected to a high-voltage alternating-current circuit, the use of a voltage transformer (sometimes called a potential transformer) is necessary. It is not practicable to wind the voltage coil of a meter for direct connection to, say an 11,000-volt supply, because the space available on the voltage electromagnet is not sufficient to accommodate the number of turns of wire which would be necessary. Moreover it would be quite impossible to insulate adequately the winding and the terminals in such a manner as to render the meter safe to handle when the circuit to which it was connected was alive. Accordingly, a voltage transformer is always used when a meter is installed for use on a high-voltage system. In this connection potentials in excess of 660 volts are regarded as high voltage.

A voltage transformer may be defined as an instrument transformer for the transformation of voltage from one value to another, usually a lower one. The primary winding of a voltage transformer is the winding to which is applied the voltage to be measured or controlled, as the case may be. The secondary winding is the winding the terminals of which are connected to the meter or instrument. The standard voltage at the terminals of the secondary winding is 110 volts.

13.2. Construction of Voltage Transformers. Voltage transformers are frequently fitted in switchgear cubicles, and owing to the restricted space available the dimensions of the transformer must be kept down to a minimum. Clearances between conductors or other live parts, which in power transformer design are regarded as minimum values, cannot always be provided in voltage transformers, and as reliability is the first consideration it is only by skilful design and care in manufacture that safety can be assured.

A voltage transformer comprises a magnetic circuit, usually built up with iron strips assembled together to form a core on which the primary and secondary windings are mounted. The primary winding which is connected to the high-voltage supply consists of a large number of turns of a fine-gauge wire and is usually divided into a number of separate sections. The object of dividing the primary in this manner is

to limit the voltage across each section to a comparatively low value. In practice, the voltage per section does not usually exceed 1,000 volts, and frequently is much less than this figure. Each section consists of layers of wire, $\frac{3}{8}$ in. to $\frac{3}{4}$ in. wide, with a strip of paper or other insulating material to separate the layers. For mechanical reasons and in order to minimize the risk of breakage and open circuits, wire smaller than 36 S.W.G. (0·0076 in. dia.), is seldom used in the primary winding.

In voltage transformers for operation at 6,600 volts or less, it is common practice for the sections of the primary to be assembled on a tube of insulating material adjacent to the core, a second tube surrounding the sections and carrying the secondary winding. This disposition of the windings is advantageous in the case of open-type transformers since the high-voltage winding is shielded from mechanical damage by the two tubes and only the more robust low-voltage winding is exposed.

For voltages in excess of 6,600 volts this arrangement is undesirable, partly because the joints between sections which are increasing in number are inaccessible, and partly because of the increasing cost of the two tubes, both of which must be capable of withstanding the full working voltage continuously. The alternative disposition in which the secondary winding is adjacent to the core and is surrounded by the primary, is the more usual, a heavy tube separating the windings. Only a light tube separates the secondary from the core and no mechanical protection is provided over the high-voltage windings. This, however, is unnecessary since transformers for the higher voltages are protected by a tank or other enclosure containing oil or some other insulating medium.

Voltage transformers are made up in single units for connection to single-phase, two-phase or three-phase systems. The magnetic circuit of a single-phase voltage transformer may be of the core type or the shell type, somewhat similar in shape to the cores of current transformers shown in Fig. 195 on page 414. The windings are usually disposed on both limbs of the core-type carcase and on the middle limb of the shell-type. The shell-type construction is seldom employed where the system voltage exceeds 3,300 volts. Two-phase voltage transformers are required occasionally and if made up as single units, a three-limbed core is used, similar in shape to the shell-type current transformer core. The windings are disposed on the two outer limbs and as the middle limb carries the common flux for both phases it is of greater sectional area than the outer limbs. The more usual practice however is to use

two separate single-phase transformers on a two-phase system. Three-phase voltage transformers are built up on three-limbed cores, all the limbs being of equal cross-sectional area. Each limb carries the primary and secondary windings for one phase of the supply, and when used for connection to a meter, the connections are usually arranged star/star.

When a transformer is switched on to a live line, the voltage between the turns of the high-voltage winding adjacent to the line terminal may be raised momentarily to a value many times the normal. A similar condition may arise as a result of switching operations elsewhere on the system and in an extreme case the voltage between successive end turns may reach a very high value; such a condition persists only for a minute fraction of a second but it imposes an additional stress on the inter-turn insulation which in the absence of precautionary measures may result in failure. The stress on the insulation is greatest between the first and second turns counting from the end of the high-voltage winding and diminishes turn by turn until, at some distance from the end, the abnormal stress disappears entirely.

In power transformer practice it is customary to reinforce the insulation between the end turns of the high-voltage winding and about ten per cent. of the winding may be dealt with in this manner. This reinforcement is graded and is heaviest on the first few turns, but progressively less and less is added until finally reinforcement ceases. In a voltage transformer of comparable voltage, the number of turns in the high-voltage winding is very much greater than in a power transformer and reinforcement of the insulation on ten per cent. of the turns would be impracticable. It is customary however to reinforce the insulation on the whole of the turns in the first section of the winding. As an additional precaution, a reactance coil consisting of a few turns of heavily-insulated wire is sometimes connected between the high-voltage terminal and the end of the high-voltage winding. This reactance acts like a cushion between the line and the high-voltage winding and reduces the severity of the transient stresses without adding appreciably to the dimensions of the transformer or impairing its accuracy.

13.3. Insulation of Voltage Transformers. Three methods of insulating the windings of voltage transformers are in general use, the transformers being referred to as dry-type, oil-immersed or compound-filled respectively. The particular method adopted will depend upon the conditions under which the transformer will be used. Dry-type transformers have windings which are effectively insulated with lappings of silk or cotton

tape. Quite frequently they are installed without any protective housing, in which case they may also be referred to as open-type. The windings of dry-type transformers are usually dried under vacuum, impregnated with insulating varnish under pressure, and finally baked at a temperature sufficiently high to drive out all the solvent contained in the varnish and to harden the residue. This treatment prevents the absorbtion of moisture into the windings and reliable operation may be expected on operating voltages up to 3,300 volts. In extreme cases, and under favourable conditions, this construction can be adopted for voltages up to 6,600 volts, provided that the transformer is to operate in a perfectly dry situation.

An oil-immersed voltage transformer (sometimes incorrectly described as oil-cooled), is provided with a tank or other enclosure to contain the core and windings, and this is filled with oil to a point well above the windings and the lower part of the high-voltage terminals. The oil is provided as a means of insulation and not as a cooling medium, since the temperature rise when a transformer is carrying its rated burden is usually very low as compared with that of a power transformer. Care must be taken in the design and construction of the transformer to provide means whereby the oil can penetrate to the innermost parts of the windings. Any air pockets which may remain will be a source of weakness and danger, and may result ultimately in failure of the insulation in the region of the air-pocket.

Owing to the very high electric strength of transformer oil the clearances between the high-voltage windings and the core or tank can be very much reduced below what is essential in the absence of oil. It follows that an oil-filled transformer can be made smaller than a dry-type of comparable voltage, at any rate for voltages in excess of 6,600 volts or thereabouts. Free circulation of the oil around the windings is desirable as this permits the small amount of heat developed to be rapidly dissipated. Further, it prevents any undue rise in temperature should the transformer be subjected to a moderate overload for a prolonged period. It is important to note that the working voltage should not be applied to a transformer designed for oil immersion unless the windings are completely submerged in oil, otherwise a breakdown of the insulation is likely to occur.

In recent years, engineers have regarded the presence of oil in switchgear and transformers with a certain amount of disfavour owing to the supposed fire risk, and efforts have been made to eliminate inflammable oil as far as possible from apparatus installed in power

stations. Synthetic liquids which have good insulating properties and which are non-inflammable are now available as alternatives to the mineral oil which is usually employed in voltage transformers. The high cost of these liquids has prevented them from being adopted on an extensive scale, and only in cases where the entire absence of fire risk is of great importance would their use be justified. The strong solvent action of some of these liquids on the linseed-oil varnish usually adopted for impregnating the windings prevents their adoption in many instances. Of the numerous synthetic liquids now available, those known by the trade names of "Pyranol" and "Aroclor" have been used where conditions were favourable.

The amount of oil contained in the tank of a voltage transformer is comparatively small, at any rate for voltages up to 11,000 volts, and the temperature at which it is maintained is low. On the other hand, the oil in the tank of a circuit-breaker is exposed to a high-temperature arc each time the breaker operates, and this constitutes a much greater fire hazard. It is probable that the risk of initiating a fire is non-existent in the case of an oil-immersed voltage transformer, but a fire having once started at another source may be spread should the flames reach the voltage transformer. If therefore the risk of starting a fire can be eliminated from other apparatus, the oil-immersed voltage transformer may be regarded as perfectly safe in this respect.

Compound-filling instead of oil-filling may be used in some instances for voltage transformers. One form of compound which has a bitumen base is solid at normal temperature; it cannot leak from the tank either during transport or after installation and the transformer may be erected in a horizontal or a vertical position. Since there can be no circulation of the compound, the heat developed in the windings when in use cannot readily escape, and the working temperature of the transformer must of necessity be higher than in a dry-type or oil-immersed transformer of comparable rating.

If a solid-compound-filled transformer is subjected to an excessive load for a prolonged period the compound may become fluid. The compound increases considerably in volume when heated, and heat developed internally may result in the outer mass of compound becoming cracked owing to the expansion of the inner portion adjacent to the windings. Instances have been known where the tank containing the transformer has burst due to the internal pressure set up from this cause. Solid compound is seldom used as an insulating medium for voltage transformers and compound consisting of a viscous mass which

is semi-fluid at normal temperatures is available. When this latter is used the transformer must of course be maintained in an upright position to avoid leakage and the disadvantage associated with expansion on heating is absent.

13.4. Fuses and Resistors for Voltage Transformers. Voltage transformers are usually provided with fuses on the high-voltage side, two being fitted on single-phase transformers and three on three-phase. The object of the fuse is to disconnect the transformer from the line in the event of a fault developing inside the transformer and a little consideration will show that the high-voltage fuse usually fitted cannot protect the transformer itself. The current in the primary winding of a voltage transformer may be less than 50 milliamperes, probably much less; an increase in this current up to, say, five times its normal value would still be insufficient to blow a fuse of normal construction when fitted on the high-voltage side. The transformer can however be protected against overloads on the external circuit by fuses on the secondary side.

If a fault develops in a voltage transformer, this is usually due to a short-circuit between adjacent turns or layers in the high-voltage winding, a break in the wire on the high-voltage winding, or occasionally to a failure in the insulation between the winding and the core. Rarely, if ever, does a fault develp in the secondary winding. In each of the cases enumerated local heating occurs but the magnitude of the primary current does not necessarily increase immediately to such a value as to blow the fuse. The local heating increases the area of the fault and final failure may develop with great rapidity into a short-circuit. In such a case the primary current may rise in a fraction of a second to a value beyond the capacity of a normal voltage transformer fuse to clear the fault. The arc which then follows the rupture of the fuse may, in a confined space such as a switch cubicle, develop into a short-circuit between lines.

In order to avoid the consequences of a failure such as this it is customary to fit a limiting resistor in series with each fuse. This resistor may consist of a high-resistance wire embedded in vitreous enamel material, or alternatively a rod consisting of a mixture of carbon dust and siliceous matter moulded into a solid mass. The ohmic resistance varies according to the voltage and rating of the transformer and values ranging from 100 ohms for a 6,600-volt transformer to 1,000 ohms for a 33,000-volt transformer are usually appropriate.

The function of the resistor is to limit the current flowing into a

short-circuited transformer winding to such a value that the fuse is capable of effectively breaking the circuit. Obviously, resistors having ohmic values much higher than here suggested would be more effective in that the maximum current would be less, but a high resistance value would affect the accuracy of the transformer. The effect on the transformer error of the additional resistance inserted in series with the primary winding is the same as if the resistance of the primary winding itself had been increased by the same amount. Practical experience has shown that well-designed fuses are capable of effectively opening the circuit when resistances of the order stated are used, and at the same time the effect on accuracy is usually unimportant.

A special form of fuse designed for the protection of voltage transformers has recently been introduced by Allen West and Co. Ltd. and is intended to overcome the disadvantages usually associated with the conventional fine-wire element fuse previously referred to. The new fuse element consists of a gold layer ceramically deposited on a quartz carrier, housed in a glass tube packed with carefully-graded quartz sand, and sealed with the customary end-caps. Copper leads are soldered to the metallic layer and again to the end-caps, this ensuring positive contact. The gold layer forming the conductor is so thin that it could not exist without the quartz support to which it is fired. A short constriction in the conducting path localizes the heat which is developed when a slowly-rising fault such as a progressive inter-turn short-circuit occurs in a transformer winding, and final rupture of the fuse occurs at this point. The constriction is precisely dimensioned for calibration of the minimum fusing current. Fuses are available for use on 3,300, 6,600 and 11,000-volt circuits having standard current ratings of 50, 100 and 200 milliamperes, the minimum fusing current being three times the rated current.

13.5. Multi-Range Voltage Transformers. Multi-range transformers are used in laboratories and test-rooms in order to increase the range of measurement of voltage-actuated instruments or as standards of comparison in carrying out tests on other voltage transformers. A number of methods for providing two or more ranges in a single transformer are available. These include a tapped primary winding, a tapped secondary winding, a series-parallel arrangement of primary windings, or a combination of two of these methods.

A tapped primary may be used where the lowest ratio does not differ greatly from the highest, such as for example 12,000–11,000–10,000/110 volts. Reasonably close agreement between the errors on

the various ranges, which is a desirable feature, can be obtained but if the tapping results in the symmetrical distribution of the winding on the core being seriously disturbed the errors on the various ranges may differ considerably, more particularly the phase displacement errors. A dual-ratio transformer having ranges of 11,000–3,300/110 volts would not be very satisfactory if made with a tapped primary, as the whole of the effective portion of the primary in use on the lower voltage range would be concentrated on one limb, assuming that a core-type transformer was used. A better performance might be expected from a shell-type transformer as the windings would still be symmetrical, but the employment of a shell-type magnetic circuit is unusual for voltages as high as 11,000 volts.

A multi-range transformer with tapped primary for use on high voltages is cumbersome and expensive if three or more ranges are required. The number of high-voltage terminals required is one more than the number of ranges, and accordingly a four-range transformer would require five high-voltage terminals. In such a case a tapped secondary winding is probably preferable; the objection to several primary tappings is not serious if the maximum voltage range does not exceed, say, 3,300 volts, as the space required to accommodate the high-voltage terminals is then comparatively small.

A tapped secondary winding can be used to provide all the ranges referred to in the previous paragraphs, and usually with more satisfactory results as regards accuracy: it does not suffer to the same extent from errors due to unsymmetrical distribution of the windings. In the case of a single-phase core-type transformer the primary will naturally be distributed equally on both limbs; it is also comparatively easy to arrange for the secondary to be distributed fairly equally, no matter which tapping is in use. Since the space required to accommodate the secondary is small, an alternative to the tapped secondary is the provision of a separate secondary for each range. By superimposing one secondary on another the winding-space occupied by each is nearly identical and the variation between the errors on the different ranges is considerably reduced.

The permissible burden which may be imposed on a transformer with tapped primary or tapped secondary is different on every range and varies approximately as the square of the primary voltage if the errors are to remain within the same limits on all ranges. Thus, a transformer having ranges of 11,000–6,600–3,300/110 volts and rated at 100 volt-amperes on the 11,000 volt range, would be capable of

supplying only 36 volt-amperes on the 6,600 volt range and 9 volt-amperes on the 3,300 volt range.

A series-parallel arrangement of primary windings has advantages from the point of view of accuracy. With this arrangement, the errors on every range will be substantially the same and also the volt-ampere ratings. For moderate voltages up to say 2,200 volts, three ranges can be provided such as 2,200–1,100–550/110 volts or 880–440–220/110 volts by means of link connectors and without excessive cost. Eight primary terminals are necessary for three voltage ranges as above, and these are connected to four primary sections. For the highest range all the sections are connected in series and for the lowest all are in parallel. The intermediate range is obtained by connecting one pair of coils in parallel, these being in series with the other pair in parallel.

For voltages in excess of 3,300 volts, the cost of transformers with three voltage ranges obtained by means of series-parallel connections rises rapidly owing to the disproportionate cost of the high-voltage terminals. Two voltage ranges can, however, be provided such as 22,000–11,000/110 volts, but above this voltage the cost may again become prohibitive. It will be noted that the ranges obtainable by means of series-parallel connections are in the ratio of 4 : 2 : 1 in a triple-range transformer and 2: 1 in a dual-range. On the other hand, a tapped secondary permits any odd ratios to be provided which cannot be obtained conveniently by any other means.

A multi-range transformer having a series-parallel arrangement of primary windings and a tapped secondary makes a very useful combination. The number of ranges obtainable by this means is equal to the product of the number of primary and secondary ranges. Thus, a transformer having three ranges obtained by means of series-parallel connections on the primary and two ranges by means of a tapped secondary will have six ranges in all. For example, a transformer having ranges of 2,200–1,100–550/110 volts, can by means of one secondary tapping provide additional ranges of 2,200–1,100–550/100 volts. Multi-range voltage transformers for two-phase or three-phase circuits are seldom called for and cannot be made to give the same degree of accuracy as is achieved with single-phase transformers.

13.6. Theory of Voltage Transformers. A voltage transformer is similar in constructional features to a power transformer in that it has a magnetic circuit with which is linked a primary and a secondary winding; the operating conditions however may differ somewhat. In a power transformer the primary winding is energized continuously at a

substantially constant voltage and the secondary is connected to a load which may vary between zero and the maximum which the transformer is capable of carrying. The power transformer is designed so that the regulation, or the voltage drop between these two extremes of load, is maintained within reasonable limits, and the temperature rise when carrying full load continuously does not result in damage to the insulation. With constant primary voltage a drop of five per cent. in secondary voltage between no load and full load is not unusual.

In a voltage transformer also, the primary winding is energized continuously at a substantially constant voltage, but the load or burden connected to the secondary does not vary as a rule. The permissible drop in voltage between zero and maximum burden is much smaller than the corresponding limit in a power transformer, and for this reason the voltage transformer is never loaded up in practice to anything like the extent which would be permissible if temperature rise were a limiting factor. As a matter of fact, a voltage transformer is usually capable of carrying many times its rated burden without overheating but under such conditions the permissible limits of error would be exceeded. The phase difference between primary voltage and reversed secondary voltage, which is of little practical importance in the case of a power transformer, is of paramount importance in a voltage transformer.

Two vector diagrams for a voltage transformer are given in Figs. 201 and 202. The former illustrates the conditions when the secondary is on open circuit and the latter when an inductive burden is connected across the secondary terminals; for convenience in illustration, a transformer having a nominal ratio of 1/1 is taken, also the magnitudes of some of the quantities are exaggerated in order to represent more clearly the principles involved. In Fig. 201 the condition is represented in which there is no burden connected to the secondary terminals and consequently no current in the secondary circuit. A voltage V_P applied to the primary terminals causes an exciting current I_O to flow in the primary winding. This current is made up of two components, I_M the magnetizing current and I_C the core-loss current which respectively magnetize the core and supply the core losses. The core flux Φ linked with the primary and secondary windings induces an e.m.f. in each, the values of which $-E_P$ and E_S are equal (assuming equality in turns). That induced in the primary winding ($-E_P$) may be regarded as a back e.m.f. since it opposes the applied voltage V_P.

The exciting current I_O flowing through the primary has to-

overcome the resistance and reactance of the winding, resulting in an impedance drop equal to the vector sum of $I_O R_P$ and $I_O X_P$. The primary voltage V_P is therefore made up of the vector sum of the three

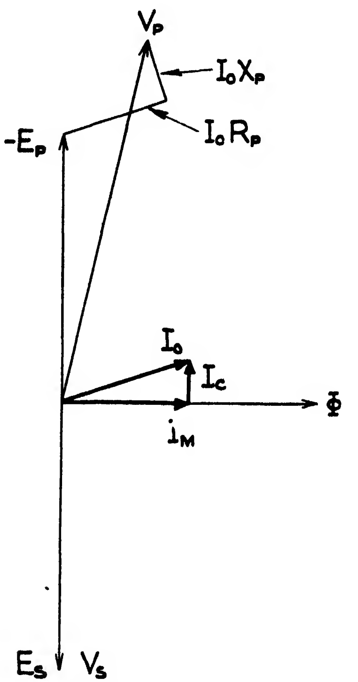


FIG. 201.—Vector diagram for voltage transformer with secondary on open circuit.

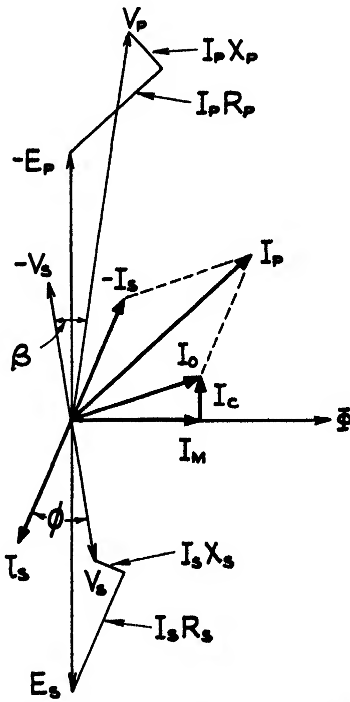


FIG. 202.—Vector diagram for voltage transformer having an inductive burden.

V_p = primary voltage.		$-E_p$ = primary induced e.m.f.	
V_s = secondary voltage.		E_s = secondary induced e.m.f.	
I_m = magnetizing current.		R_p = primary resistance.	
I_o = exciting current.		R_s = secondary resistance.	
I_c = core loss current.		X_p = primary reactance.	
I_p = primary current.		X_s = secondary reactance.	
I_s = secondary current.		Φ = core flux.	

ϕ = phase difference between secondary current and voltage.
β = phase difference between primary and reversed secondary voltage.

components $-E_P$, $I_O R_P$ and $I_O X_P$. Since there is no current flowing in the secondary winding the induced secondary e.m.f. E_S, coincides with the secondary terminal voltage V_S in magnitude and phase.

In Fig. 202 the condition is represented in which an inductive

burden is connected to the secondary terminals. The secondary current I_S lags by an angle ϕ behind the secondary terminal voltage V_S. This current has to overcome the impedance of the secondary winding, resulting in a drop in voltage equal to the vector sum of I_SR_S and I_SX_S. The voltage applied to the burden is therefore equal to the vector difference between the induced secondary e.m.f. and the impedance drop in the secondary winding.

The connection of a burden across the secondary terminals and the consequent current which flows through the same results in an increase in the primary current represented by a component $-I_S$ equal in magnitude to and opposite in phase from the secondary current I_S. The primary current I_P is the resultant of the two components $-I_S$ and I_O. This current flowing through the primary winding causes an impedance drop equal to the vector sum of I_PR_P and I_PX_P which, when added to the induced primary e.m.f. $-E_P$, gives the terminal voltage V_P necessary for this particular burden.

The ratio error of the transformer is proportional to the difference between the primary voltage V_P and the vector of reversed secondary voltage $-V_S$. The angle β between V_P and $-V_S$ is the phase difference angle, and in the example the vector of reversed secondary voltage is leading the primary voltage. This is quite a usual condition, but in some circumstances depending upon the magnitude and power-factor of the burden, the reversed secondary voltage may lag behind the primary voltage. As mentioned in an earlier paragraph, the magnitudes of some of the quantities have been exaggerated in the diagram in order to depict more clearly the principles involved. In actual practice, the difference between the length of the vectors V_P and $-V_S$ would be much less than shown and the angle β between the vectors would also be much smaller.

The inherent errors of a voltage transformer are due partly to the characteristics of the magnetic circuit and partly to the impedance of the windings; with no burden connected to the secondary, the no-load errors are due almost entirely to the exciting current. By careful design and by operating the core at a comparatively low flux density the no-load errors can be minimized. The on-load errors are due in the main to the influence of resistance and reactance in the windings; in order to reduce reactance to a minimum it is necessary to avoid magnetic leakage and this can be achieved by close association of one winding with another and with the core: the latter must also be kept as short as possible. Unfortunately the requirements of insulation, more particularly

in high-voltage transformers, necessitate ample spacing of the high-voltage winding from the secondary and core. Thus the design of a voltage transformer must be a compromise between the conflicting requirements of accuracy and reliability.

13.7. Classes and Rated Burdens of Voltage Transformers. The burden of a voltage transformer is the value of the load connected across the secondary terminals, expressed as the output in volt-amperes at the rated secondary voltage. The rated burden and the rated secondary voltage are the values of the burden and the secondary voltage respectively, marked on the rating plate. Several classes of voltage transformer are required for different purposes and some classes are made for supplying a range of burdens. Details of the various classes and their corresponding rated burdens are given in British Standard Specification for Instrument Transformers, B.S. 81: 1936, which states in Clause 23 that the rated burden of a voltage transformer shall normally have one of the values set out in Table 16 which follows. It should be noted that, above 33,000 volts, the lowest rated burden of a voltage transformer is generally not less than 200 volt-amperes per phase, irrespective of the class of accuracy. Also Classes AL and BL are intended to include only highly accurate portable instrument transformers, and the accuracies laid down for these classes are not normally applicable to instrument transformers intended for other purposes.

Not all the classes of voltage transformers listed in Table 16 are suitable for metering purposes. Transformers of Classes A or B should

TABLE 16

Rated Burdens of Voltage Transformers

Class	Rated Burden in Volt-Amperes per Phase at Standard Frequency and at Unity Power-Factor							
	Single-Phase				Three-Phase			
A		50	100	200		50	100	200
B	15	50	100	200	25	50	100	200
C	15	50	100	200	25	50	100	200
D	No standard burden				No standard burden			
AL	10				—			
BL	10				—			

be used in conjunction with Precision Grade meters and Class B in conjunction with Commercial Grade meters. Classes C and D are not suitable for use with meters if accurate registration is desirable. Classes AL and BL are intended primarily for use with indicating instruments. They can also be used with meters but are unnecessarily expensive for this purpose, and as their rated burdens are only 10 volt-amperes they will usually be found too small on this account.

13.8. Errors in Voltage Transformers. One of the functions of a voltage transformer is to deliver to the meter or instrument connected to its secondary terminals a voltage, the magnitude of which is proportional to the voltage applied to the primary terminals. Further, the secondary voltage should coincide in phase with the primary terminal voltage. The amount by which the secondary voltage differs in magnitude from exact proportionality to the primary terminal voltage is called the ratio error. The angle by which the secondary voltage differs in phase from the primary terminal voltage is called the phase difference error or the phase angle.

In an ideal voltage transformer there would be exact proportionality between primary and secondary voltage and also exact coincidence in phase relationship irrespective of the magnitude or power-factor of the burden connected to the secondary terminals. In practice this ideal cannot be achieved owing to the influence of losses in the magnetic and electric circuits of the transformer, but by careful design the losses can be kept small and the resultant errors maintained within narrow limits.

The limits of error for voltage transformers are laid down in British Standard Specification for Instrument Transformers, B.S. 81: 1936, which states in Clause 24:

"The ratio error and phase difference between primary and secondary voltages when measured under the conditions set forth in Sub-clauses (a) and (b) hereof shall not exceed the limits given in Sub-clauses (c) and (d).

"(a) The limits of error shall refer to the errors as determined at the terminals of the primary and secondary windings, excluding any protective resistors or fuses.

"(b) The impedance of the circuit connected to the secondary terminals of the transformer shall remain fixed throughout the test and shall be such as to absorb the appropriate burden at the rated secondary voltage.

"(c) Classes A, B, C, and D.—The ratio error and phase difference of a voltage transformer of Class A, B, C or D at the respective voltages, burdens and power-factors given in Table 17 shall not exceed the limits therein set out.

TABLE 17

Limits of Error for Voltage Transformers for General Use

Class	At 90% to 100% of Rated Voltage and 25% to 100% of Rated Secondary Burden at Unity Power-Factor		At 90% to 106% of Rated Voltage and 10% to 50% of Rated Secondary Burden at 0·2 Power-Factor	
	Ratio Error	Phase Diff.	Ratio Error	Phase Diff.
	+ or −	+ or −	+ or −	+ or −
A	0·5%	20 min.	0·5%	40 min.
B	1·0%	30 ,,	1·0%	70 ,,
C	2·0%	60 ,,	—	—
D	5·0%	—	—	—

"(d) Classes AL and BL.—The ratio error and phase difference of voltage transformers of Classes AL and BL, with any burden not exceeding the rated burden, and of unity power-factor, shall not exceed the respective limits set out in Table 18.

TABLE 18

Limits of Error for Voltage Transformers for Laboratory Use

Class	At any Primary Voltage down to and including 80% of the Rated Voltage	
	Ratio Error	Phase Difference
	+ or −	+ or −
AL	0·25%	10 minutes
BL	0·50%	20 ,,

"When the errors of a voltage transformer are determined by means of a test with the actual working burden, the resistance of any current-limiting resistors, fuses, or leads should be included, since the effect of the voltage drop in such accessories or leads may be considerable. The errors so determined are those at the end of the leads remote from the transformer, and under these conditions will not necessarily be within the limits laid down for the rated burden."

13.9. Terminal Markings of Voltage Transformers. The terminals of voltage transformers are marked in accordance with a system which enables one to identify readily the primary and secondary windings and the polarity of the same. Details of these markings are given in

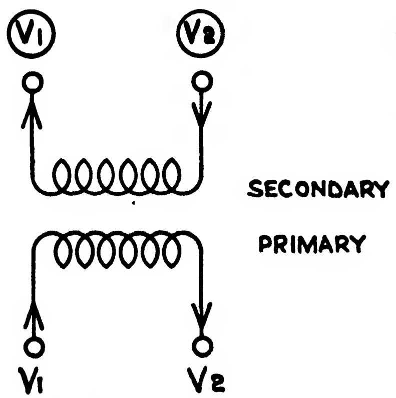


FIG. 203.—Terminal markings of single-phase voltage transformer with plain windings.

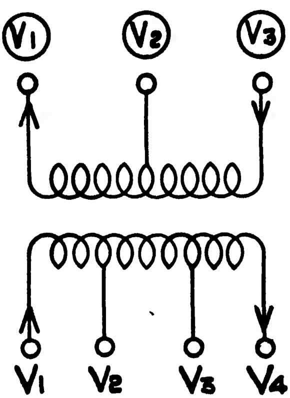


FIG. 204.—Terminal markings of single-phase voltage transformer with tapped primary and secondary windings.

Appendix K to B.S. 81: 1936. The primary terminals are distinguished by the use of capital letters with or without the addition of numerals. The corresponding secondary terminals are distinguished by similar markings each contained in a circle.

The system of marking a single-phase voltage transformer is indicated in Fig. 203. The primary terminals are marked V_1 V_2 and the secondary terminals bear similar markings (encircled). The polarity of the terminals is such that when V_1 is positive with respect to V_2, the correspondingly marked secondary terminals have similar polarities. The markings of a single-phase voltage transformer with tapped windings are shown in Fig. 204. The primary terminals are marked V_1 V_2 V_3 V_4 and the secondary markings are encircled.

The marking of a three-phase voltage transformer, connected star/star, is shown in Fig. 205. The primary terminals are marked A B C N and the secondary terminals are similarly marked with letters encircled. The terminal marked N is the neutral. There are in addition other standard arrangements of terminal markings but they are not used extensively in metering practice and consequently are not described here.

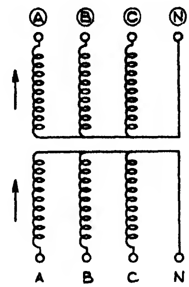


FIG. 205.—Terminal markings of three-phase voltage transformer connected star/star.

13.10. Typical Performance Data. In the Tables which follow, figures are given which show the variations in ratio error and phase displacement in voltage transformers arising in practice as a result of variations in burden or loading conditions. The tests were carried out on several types of single-phase and three-phase transformers and the results may be compared with the limits of error specified in B.S. 81: 1936, details of which will be found in Tables 17 and 18 on page 449. All the transformers concerned in these tests were manufactured by Chamberlain and Hookham Ltd.

TABLE 19

Tests on Single-Phase Voltage Transformer
Ratio: 33,000/110 Volts, 50 Cycles per Second

Burden	Ratio Error	Phase Diff.
Zero	+0·6%	2 min. lead
100 VA	+0·4%	4 min. lag
200 VA	+0·3%	8 min. lag

The test results given in Table 19 show the performance of a single-phase voltage transformer, Class B, ratio 33,000/110 volts, 50 c/s, and rated at 200 volt-amperes. It will be noted that the total change in the errors between zero and rated burden is 0·3 per cent. in ratio and 10 minutes in phase difference; also the phase error which is leading at zero burden is lagging at 100 volt-amperes burden. With a burden of approximately 33 volt-amperes, the error in phase difference would

be zero. By a slight adjustment in the turns ratio, the transformer could be made to comply with the limits of error for a Class AL transformer.

TABLE 20

Tests on Dual-Ratio Voltage Transformer
Ratios: 22,000–11,000/110 Volts, 50 Cycles per Second

Trans. Ratio	Burden	Ratio Error	Phase Diff.
22,000/110 V.	Zero	+0·9%	6 min. lead
22,000/110 V.	200 VA	+0·4%	Zero
11,000/110 V.	200 VA	+0·4%	Zero

The test results given in Table 20 were obtained on a single-phase transformer having two primary sections arranged for series-parallel connection. With the sections in series, the ratio 22,000/110 volts is obtained and with the sections in parallel the ratio is 11,000/110 volts. As might be expected, the errors are identical on both ratios. Because of the magnitude of the ratio error with zero burden this transformer is rated as Class B, but by suitable adjustment of the turns ratio the classification could be raised to Class A, or BL, or AL, as the phase angle is within the limits set for these classes and would not be changed appreciably by an alteration in the turns.

TABLE 21

Tests on Three-Phase Voltage Transformer
Ratio: 6,600/110 Volts, 50 Cycles per second
Rated Burden: 50 VA per Phase

Phase on Test	Burden per Phase	Ratio Error	Phase Diff.
B–C Leading	Zero	+0·7%	16 min. lead.
B–C Leading	50 VA	–0·9%	8 min. lead.
B–A Lagging	Zero	+1·0%	24 min. lead.
B–A Lagging	50 VA	–0·6%	16 min. lead.

The test results given in Table 21 show the performance of a three-phase voltage transformer, Class B, ratio 6,600/110 volts, 50 c/s, rated at 50 volt-amperes per phase and loaded on two phases only. It will be noted that the application of the rated burden to both the loaded phases results in a change of the ratio error by 1·6 per cent. and a reduction in the leading phase angle of 8 minutes in each case.

TABLE 22

Tests on Three-Phase Voltage Transformer with Resistance in Series with Primary Winding
Ratio: 440/110 Volts, 50 Cycles per Second
Rated Burden: 110 VA per Phase

Phase on Test	Burden per Phase	Ratio Error	Phase Diff.
A–B	10 VA	+0·4%	33 min. lead.
A–B	100 „	–2·9%	18 „ „
B–C	10 „	+0·1%	29 „ „
B–C	100 „	–3·2%	16 „ „
C–A	10 „	+0·1%	40 „ „
C–A	100 „	–3·1%	27 „ „

The figures in Table 22 are included in order to show the detrimental effect of an excessive amount of resistance in series with the primary winding. The transformer under test was a three-phase voltage transformer, ratio 440/110 volts, 50 c/s, rated at 100 volt-amperes per phase. Fuses were fitted in each phase of the primary, the type used being that normally fitted on 6,600-volt transformers. These fuses were wired with No. 42 S.W.G. Eureka wire and had a resistance of 10·6 ohms per phase. Reference has been made in Section 13.4 to the use of resistors and it has been pointed out that a resistance of relatively low value is not detrimental to the performance of the transformer. The effect of the resistance of the fuse is quite negligible on a 6,600-volt transformer and in fact the effect of 100 ohms is quite small. In this case however, the primary is wound for 440 volts and a resistance of 10·6 ohms inserted in each phase is relatively several times the value of the series resistor used with a 6,600-volt transformer. The effect of this

disproportionate resistance value is shown in the large change in the ratio error between 10 and 100 volt-amperes burden, and also in the excessive initial value of the phase angle. The point to be noted in this connection is that if primary fuses are fitted on transformers for comparatively low voltages, the resistance of the fuses must be kept low in order to minimize errors.

APPENDIX

Numerous references have been made in this volume to British Standard Specification for Electricity Meters, B.S.37: 1937 and to British Standard Specification for Instrument Transformers, B.S.81: 1936. Both these specifications have been, and at the time of writing still are, in process of revision. Publication of revised editions may be expected in the near future and as changes in form and substance are contemplated, it may not be out of place to refer briefly to these.

The meter specification B.S.37: 1937 is a single document covering the requirements for all types of motor meters, D.C. and A.C. In the revised edition the specification is to be divided into nine sections arranged as follow:

Section 1. General clauses applicable to all types of meter.
„ 2. Single-phase two-wire whole-current credit meters.
„ 3. Single-phase two-wire prepayment meters.
„ 4. Polyphase whole-current, and single-phase and polyphase transformer-operated meters.
„ 5. Single-phase and polyphase precision meters.
„ 6. Direct-current credit meters.
„ 7. Direct-current prepayment meters.
„ 8. Portable meters.
„ 9. Kilowatt-demand meters.

Revision of Sections 1 and 2 is completed and these are to be published immediately under the designation B.S.37: 1952. The remaining sections will follow at intervals as completed.

Section 1 comprises definitions and general clauses which are applicable to all types of meter. In the main, these clauses have been abstracted from BS.37: 1937 and do not differ to any substantial extent from the originals. There have been also a few additional clauses. No comment is called for concerning this section but it should be noted that the numbering of the clauses no longer corresponds to the numbering in the original specification.

Section 2 is concerned with the largest class of meters in everyday use, namely Single-phase Two-wire Whole-current Credit-type Meters not exceeding 80 amperes maximum marked current. Important changes in existing practice are introduced in this section. The first of

these changes has reference to standard ratings and markings (in ampères). Hitherto, whole-current meters have been rated at 2·5, 5, 10, 25 and 50 amperes, and long-range A.C. meters so marked have been required to carry continuously, currents up to 100 per cent. in excess of the marked current. New ratings of 10, 40 and 80 amperes are to take the place of the foregoing and the marked current now represents the maximum current which the meter is required to carry continuously.

The range of measurement covered by B.S.37: 1937 is from twice the marked current down to $\frac{1}{20}$ of marked current at unity power-factor, that is to say, an effective range of 40/1 in terms of maximum to minimum current. In the revised specification the range is from marked current down to $\frac{1}{60}$ of marked current at unity power-factor or an effective range of 60/1. Thus, there is an increase of 50 per cent. in the total range of measurement. Marked current in the revised specification corresponds roughly to three times marked current in B.S.37: 1937, and similarly, $\frac{1}{60}$ load corresponds to the old $\frac{1}{20}$ load.

Because the marked current is now the maximum current which the meter is required to carry continuously, a number of clauses based on the earlier definition have been altered. These include clauses relating to speed of rotation, power losses in the meter current circuit, limits of error, minimum running current, energy register and several others. At first glance it may appear that there has been some relaxation in the requirements, but in fact in most instances the conditions for compliance with the specification are more severe. For example, in B.S.37: 1937, the power loss in the current circuit of a 10-ampere meter must not exceed 1·5 watts at the marked current. The corresponding figure in the revised specification is 8 watts which may appear to be a liberal increase. But bearing in mind that the revised value of the marked current is approximately three times the previous value and that the losses vary as the square of the current, a comparable value in this instance would be nine times the previous value, that is, 13·5 watts. Thus, instead of an apparent increase in the permissible power loss, there is actually a considerable reduction for comparable current values.

The limits of error at unity power-factor are the same ($\pm$ 2·0 per cent.) in the old and the revised specifications. At 0·5 power-factor the maximum plus error must now not exceed 2·0 per cent. at any load, whereas previously an error of plus 2·5 per cent. was permissible at loads corresponding to $\frac{1}{30}$ of marked current and above $\frac{5}{12}$ of marked current. The maximum error in the minus direction at 0·5 power-

factor is 2·5 per cent. It will be observed that these limits of error now extend over a range 50 per cent. greater than hitherto. In view of the fact that current electromagnet braking is increasing rapidly at the upper end of the load curve, the margin between the actual error and the permissible limit in the minus direction must in many cases be very small, particularly at 0·5 power-factor.

The clause relating to facilities for adjustment has been clarified and the available range called for in the brake-magnet adjustment on delivery to the purchaser has been reduced to more reasonable proportions. There is usually some interaction between the low-load and inductive-load adjustments, an alteration in either having some effect on the other. A new clause entitled "Independence of adjustment" has now been introduced, specifying limits to the extent of the mutual interference.

The Addendum to B.S.37: 1937 dated June 1946, relating to dimensional standards for commercial credit-type single-phase meters, which became mandatory as from January 1948, has now been incorporated in the specification. The diameter of the cable holes in the main terminals has been fixed at $\frac{5}{16}$ in. for all current ratings, instead of the dimensions previously in force.

The instrument transformer specification B.S.81: 1936 includes within its scope, current and voltage transformers for use with electrical measuring instruments, electricity meters and certain protective devices such as relays and the like. To a certain extent the requirements for these various services are conflicting and it is considered desirable that they should be segregated. Accordingly, transformers for use with protective devices have been considered in one section of the specification and a further section is to be devoted to the special requirements of indicating instruments and meters. Revision of the latter section is at present in progress but no information concerning this is yet available.

When the Electricity Supply (Meters) Act, 1936, was accepted in Parliament, provision was made that all meters on circuit on the Appointed Day should be deemed to be certified meters during a period of ten years thereafter. This was to enable supply authorities to overtake the arrears in the work involved in exchanging old meters on consumers' premises for duly certified meters. Owing to the outbreak of war the work was not completed in the time anticipated and this transitional provision was amended in section fifty-two of the Electricity Act, 1947, by extending the period to fifteen years. That period has now

lapsed and still the work is not completed. In November 1951, a Bill was laid before the House providing for a further extension of five years, making twenty years in all. This Bill if passed into law, as presumably it will be in 1952, will be known as the Electricity Supply (Meters) Act, 1951.

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